AN INVESTIGATION OF THE S/N FATIGUE
LIFE GAGE

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by

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Submitted to the Department of Naval Architecture and Marine Engineering on May 17, 1968, in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional Degree, Naval Engineer.

ABSTRACT

The S/N fatigue life gage is a small sensor which is similar in appearance to a foil strain gage. The S/N fatigue life gage is bonded to the surface of a mechanical structure using standard strain-gage techniques. The S/N gage changes resistance permanently as a continuous function of fatigue experience. This gage was developed by Mr. Darrell R. Harting of the Boeing Company, Seattle, Washington. The gage is produced commercially by Micro-Measurements, Inc. and distributed by W.T. Bean, Inc., Detroit, Michigan.

This investigation describes the results of a series of reverse bending tests on S/N fatigue life gages which were mounted on Ti-6Al-4V titanium specimens. Each S/N gage was subjected to various constant strain loadings for varying numbers of cycles.

The results of this investigation show that the performance of the S/N fatigue gage under random cyclic loading is predictable. Another result of the tests indicates that the S/N gage experiences an above normal increase in resistance well in advance of actual gage failure. Finally it was observed that a decrease in S/N gage resistance will occur: immediately after the mean cyclic strain level is lowered; and whenever the gage is subjected to any substantial rest period.

Thesis Supervisor: W. M. Murray

Title: Professor of Mechanical Engineering

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Mr. R.B. Melton (Massachusetts Institute of Technology)

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SYMBOLS AND DEFINITIONS

A	distance from clamp to end of notched section on specimen
B	represents a consolidation of terms - see equation (6)
c	distance to outer material fiber from neutral axis
CPM	cycles per minute
E	Young's modulus of elasticity
GF	gage factor
I_1	section 1 moment of inertia
I_2	section 2 moment of inertia
L	length measured in x-direction
M	bending moment
N	number of cycles of a specified character which an item has endured at any time in its fatigue/stress history
n	non-linearity factor (dimensionless)
P	load
psi	pounds per square inch
Rg	gage resistance
ΔR	increment of resistance
x	arbitrary distance
y	beam deflection
y'	first derivative of y with respect to x
y"	second derivative of y with respect to x
ε_c	compressive strain
ε_g	strain at gage
$\varepsilon_{R\text{-}obs}$	observed cyclic strain
$\varepsilon_{R\text{-}calc}$	calculated cyclic strain
ε_T	total strain range
ε_t	tensile strain
$\Delta\varepsilon_i$	increment of indicated strain
$\mu\varepsilon$	microstrain (10^{-6} in./in.)
δ	distance from clamp to center of S/N gage
μ	micro units (10^{-6})

I. INTRODUCTION

> Fatigue - "The process of progressive localized permanent structural change occurring in a material subjected to conditions which produce fluctuating stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations."*

The fatigue property of a metal or a structure is not some absolute quantity which can be established as some set value. The failure of structures by the mechanism of fatigue has been under study for many years.** Recently a new dimension in the field of fatigue research has emerged in the form of a fatigue damage indicator. Several such fatigue damage indicators are presently being manufactured. The first successful indicator and the one in the most advanced state of development is the -S/N-[1)] FATIGUE LIFE GAGE. It was developed by Mr. Darrell R. Harting of the Boeing Company, Seattle, Washington (4). The gage is being produced commercially by Micro-Measurements, Inc. and distributed by W. T. Bean, Inc., Detroit, Michigan.

The S/N fatigue gage is a small sensor resembling a foil strain gage. A description of the gage is given in Appendix B. The S/N gage is bonded to the surface of a mechanical structure using standard strain-gage techniques. The location of the gage is critical. It must be mount-

---

* The recognized definition of fatigue used in fatigue testing as listed in an official ASTM report (1).

** The study of structural fatigue is complex and beyond the scope of this investigation. An excellent treatise and bibliography on the subject may be found in Manson (9).

1) Trademark: Micro-Measurements, Inc., Romulus, Michigan.

ed at the point on the structure where the principal fatigue damage will occur. The S/N gage changes resistance permanently as a continuous function of fatigue experience. The gage is similar to a computer in that it integrates all types of loadings causing failure (i.e., constant, cycling and/or random) and stores this information as a permanent and up-to-date record of effective fatigue damage. Permanently connected read-out instrumentation is not necessary with this gage. It may be interrogated periodically using simple instruments of the ohmmeter or wheatstone bridge variety (16).

In a recent report on the application of a double linear damage rule to cumulative fatigue, Manson (10) identified the subject of cumulative fatigue damage as being "extremely complex". At present the theoretical prediction of fatigue damage does not provide an acceptable prediction of fatigue life in a varying stress field. Until recently, the most widely known and used procedure was the cumulative fatigue damage concept, $\Sigma \frac{n}{N}$, developed by Miner (11). This concept showed fatigue damage accumulating at a linear rate. Since its inception this rule has proven adequate however, it has not been too accurate. Christensen and Bellinfante (2) state that fatigue damage to structures progresses at an exponential rather than a linear rate, and that the effect of prior history will greatly alter a material's fatigue life.

The methods and techniques proposed in the last two decades to supplement the Miner Rule are too numerous to list.* Nevertheless, some of the most promising fatigue damage prediction methods are:

a) The Mean Damage Rate Method (7);

b) Henry's formula for damage propogation (5);

c) The Double Linear Damage Rule by Manson, Freche and Ensign (10).

With the advent of the S/N fatigue gage a new and more direct path is opened to the prediction of fatigue damage. The S/N gage may be em-

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* An excellent bibliography on the various proposed fatigue damage theories is contained in Manson's paper on this subject (10).

ployed in collecting data to establish the validity of a particular fatigue damage theory. The S/N gage will obviate the necessity of maintaining strict loading histories of structural members susceptible to fatigue. The gage is recognized as still being in the infancy of its development. Despite this fact however, the S/N gage is presently one of the most accurate fatigue damage monitors of in-service mechanical structures available in the world today.

II. OBJECTIVES

The primary objective of this investigation is:

1. To ascertain if the performance of the S/N gage under cyclic loading can be predicted from the S/N gage's known behavior when subjected to various constant strain loadings.

The secondary objectives of this investigation are:

1. To accumulate cyclic and constant strain fatigue data for the titanium alloy Ti - 6Al - 4V;
2. To study the log-log plot of S/N gage ΔR vs. N immediately prior to and at gage failure; and
3. To determine if a S/N gage mounted on a Ti - 6Al - 4V specimen experiences any resistance decrease as the average strain level is lowered.

III. PROCEDURE

In pursuing the objectives of this investigation a series of tests were conducted. Each test and associated specimen were serialized. A summary of each test and corresponding specimen number may be found in Appendix D. A description of all equipment used in this investigation is given in Appendix B.

General Procedure

The selection and preparation details of the S/N fatigue gage specimens can be found in Appendix A. Except for two aluminum specimens, all tests were conducted with titanium specimens. The S/N fatigue machine was slightly modified to insure that the results of this investigation are comparable with previous test data. These modifications are:

a) The clamping block spacer plate was remachined to permit the specimen to deflect equally from either side of the neutral position;

b) A small steel pin was tapped into the fly-wheel. The pin turned a detached five-digit mechanical counter;

c) A terminal strip was affixed to the top of the clamping block. The S/N gage leads were attached to the terminal strip which was permanently connected to the read-out instrumentation.

The specimen was placed in the clamping block such that the fatigue gage was at a specified distance from the clamp. The location of the clamping block was then varied to one of three different positions in order to alter the average cyclic strain level. The portable strain indicator was zeroed with the specimen in the neutral position for zero reference.

All specimens were cycled by hand during the first twenty cycles

and at those times when a specific cycle number was required. At all other times the variable speed electric motor operated at a constant bending rate of 1000 CPM. Resistance change readings were taken with the specimen in its neutral position. Periodically the specimen and fatigue gage were inspected under magnification to detect any irregularities or cracks. Fatigue tests were terminated when one or more of the following events occurred:

FAILURE

a) S/N gage resistance change exceeded 10% of initial gage resistance;

b) Equivalent gage life exceeded 10^6 cycles;

c) S/N fatigue gage failure.

ΔR versus N data was plotted on log-log paper for comparison with the manufacturer's performance curves (Figure I).

Specific Test Procedures

Test # 1: A FAE strain gage of the same physical characteristics as the FWA-01 gage was mounted on the flat side of a 0.250 inch aluminum 2024-T4 specimen. The specimen was hand cycled from a compressive to a tensile loading with the clamping block in Position # 1. The purpose of this test was to determine the average cyclic strain level for a 0.250 inch aluminum specimen in Position # 1.

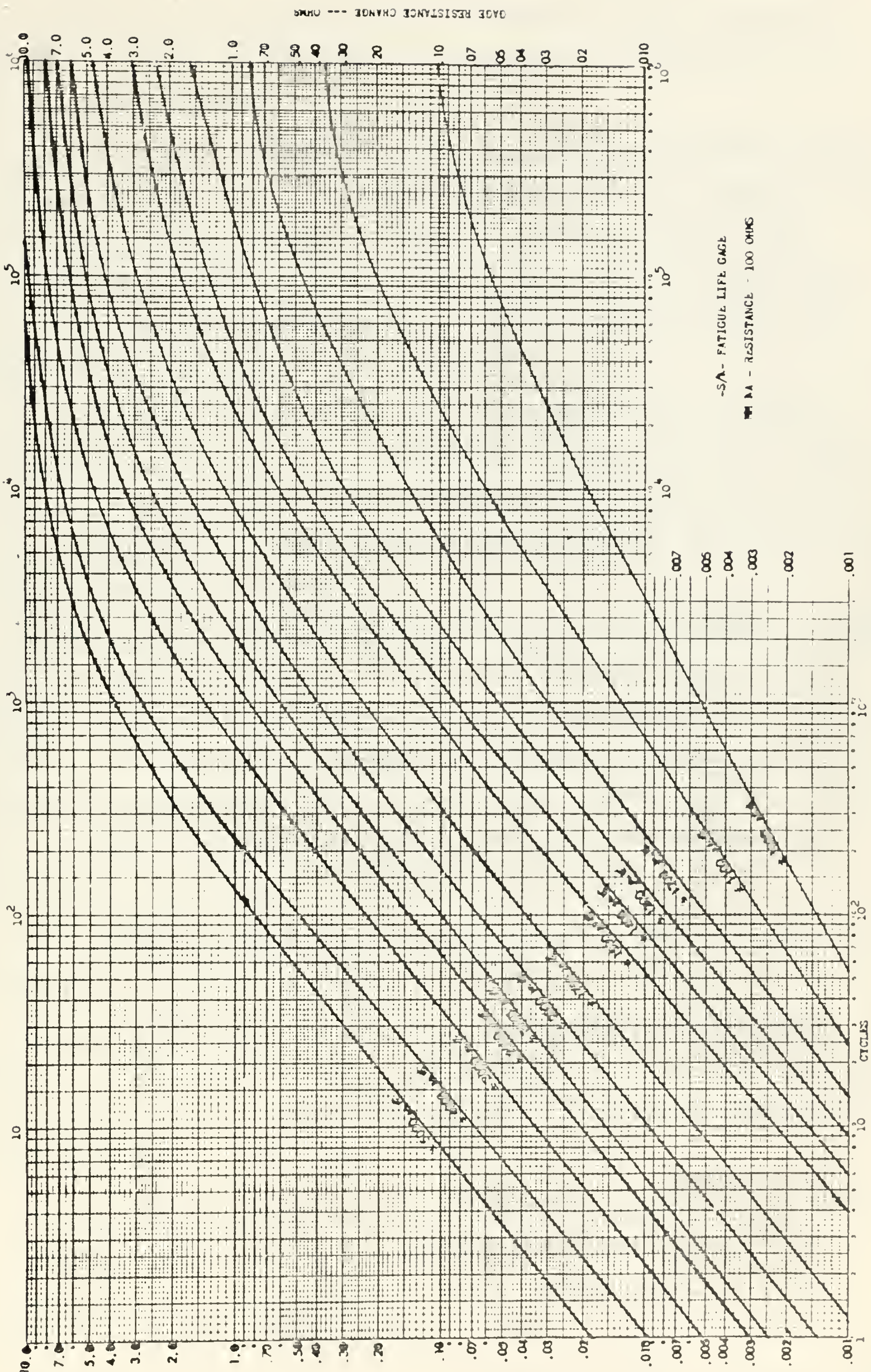
Test # 2: An EA strain gage of the same physical characteristics as the FWA-01 gage was mounted on the flat side of a 0.175 inch titanium Ti - 6Al - 4V specimen. In each of the three clamping block positions the specimen was alternately cycled from a compressive to a tensile load.

The purpose of this test was to calibrate each of the three clamping block positions with a 0.175 inch titanium specimen.

Test # 3: This test was conducted with a FWA-01 fatigue gage mounted on a 0.250 inch aluminum 2024-T4 specimen in clamping block position # 1.

The purpose of this test was to relate S/N fatigue data obtained

FIGURE I


GAGE RESISTANCE CHANGE --- OHMS
-S/A- FATIGUE LIFE GAGE
AA - RESISTANCE - 100 OHMS
CYCLES

with the manufacturer's data. Such a correlation would be indicative of proper fatigue gage application and resistance change measurement techniques. This test was necessary to validate the fatigue data obtained in subsequent tests.

Tests # 4 and 5: These tests were conducted with a FWA-01 fatigue gage mounted on a 0.175 inch Ti - 6Al - 4V specimen. The clamping block was alternately rotated between # 1 and # 2 positions with a fixed number of fatigue cycles in each position. The tests were direct opposites in that Test # 4 started in the low strain position while Test # 5 commenced in the higher strain position.

One intention of these tests was to correlate the S/N fatigue data with the manufacturer's performance curves and recommended evaluation technique for response to block-cycling (16). In addition, data could be obtained on S/N gage life as a function of the order in which the specimen was strain loaded.

Tests # 6 and 7: These tests were conducted with a FWA-01 fatigue gage mounted on a 0.175 inch Ti - 6Al - 4V specimen. Clamping block positions # 1 and # 3A were used. In test # 6 the specimen was cycled in position # 1 until ΔR = 1.0 ohms. The specimen was then subjected to reverse bending in position # 3A. Test # 7 was exactly opposite to Test # 6 in all respects except late in gage life when the clamping block was relocated to position # 3A to accelerate failure.

The purposes of these tests were identical to those of tests # 4 and 5 above.

Test # 8: This test was conducted with a FWA-01 fatigue gage mounted on a 0.175 inch Ti - 6Al - 4V specimen. The test was identical in procedure to test # 7 except that position # 3B was utilized in lieu of position # 3A.

During test # 7, erratic ΔR values were noted when the specimen was in position # 3A. In order to examine the significance of these variations, this test was conducted with a slight variation in the upper limit of average cyclic strain.

Tests # 9 - # 12: These tests were conducted with a FWA-01 fatigue gage mounted on a 0.175 inch Ti - 6Al - 4V specimen. Clamping block

positions # 1, # 2 and # 3B were randomly used. The clamping block rotation sequence was varied from test to test. Determination of when to shift the position of the block at a specified ΔR was based upon the technique recommended by the manufacturer (16).

The purposes of these tests were similar to those of tests # 4 and # 5.

<u>Tests # 13 and # 14:</u> These tests were conducted with a FWA-01 fatigue gage mounted on a 0.175 inch Ti - 6Al - 4V specimen. Clamping block positions were varied in order, commencing at the highest strain level - position # 3B. Clamping positions # 3B, # 2 and # 1 were utilized. The specimen was manually cycled immediately after each position shift to a lower strain level. This manual reverse bending of the specimen with corresponding continuous gage resistance measurements was continued until gage ΔR reattained the level it was at before the position shift.

The object of these tests was to investigate the apparent strain hardening that the S/N fatigue gage experiences as the average cyclic strain is changed to a lower strain level. A conversation with Mr. R.J. Whitehead of W.T. Bean, Inc. (13) indicated that the manufacturer was aware of this phenomenon but did not have any data with the S/N gage mounted on a titanium specimen.

IV. GRAPHICAL RESULTS

FIGURE

II	STRAIN CALIBRATION CURVE FOR S/N FATIGUE MACHINE
III	COMPARISON OF CALCULATED VERSUS OBSERVED STRAIN FOR FATIGUE MACHINE BLOCK POSITIONS
IV	PERFORMANCE CURVE FOR SPECIMEN A-2
V	PERFORMANCE CURVE FOR SPECIMEN T-2
VI	PERFORMANCE CURVE FOR SPECIMEN T-3
VII	PERFORMANCE CURVE FOR SPECIMEN T-4
VIII	PERFORMANCE CURVE FOR SPECIMEN T-5
IX	PERFORMANCE CURVE FOR SPECIMEN T-6
X	PERFORMANCE CURVE FOR SPECIMEN T-7
XI	PERFORMANCE CURVE FOR SPECIMEN T-8
XII	PERFORMANCE CURVE FOR SPECIMEN T-9
XIII	PERFORMANCE CURVE FOR SPECIMEN T-10
XIV	PERFORMANCE CURVE FOR SPECIMEN T-11
XV	PERFORMANCE CURVE FOR SPECIMEN T-12

FIGURE II
STRAIN CALIBRATION CURVE FOR
S/N FATIGUE MACHINE

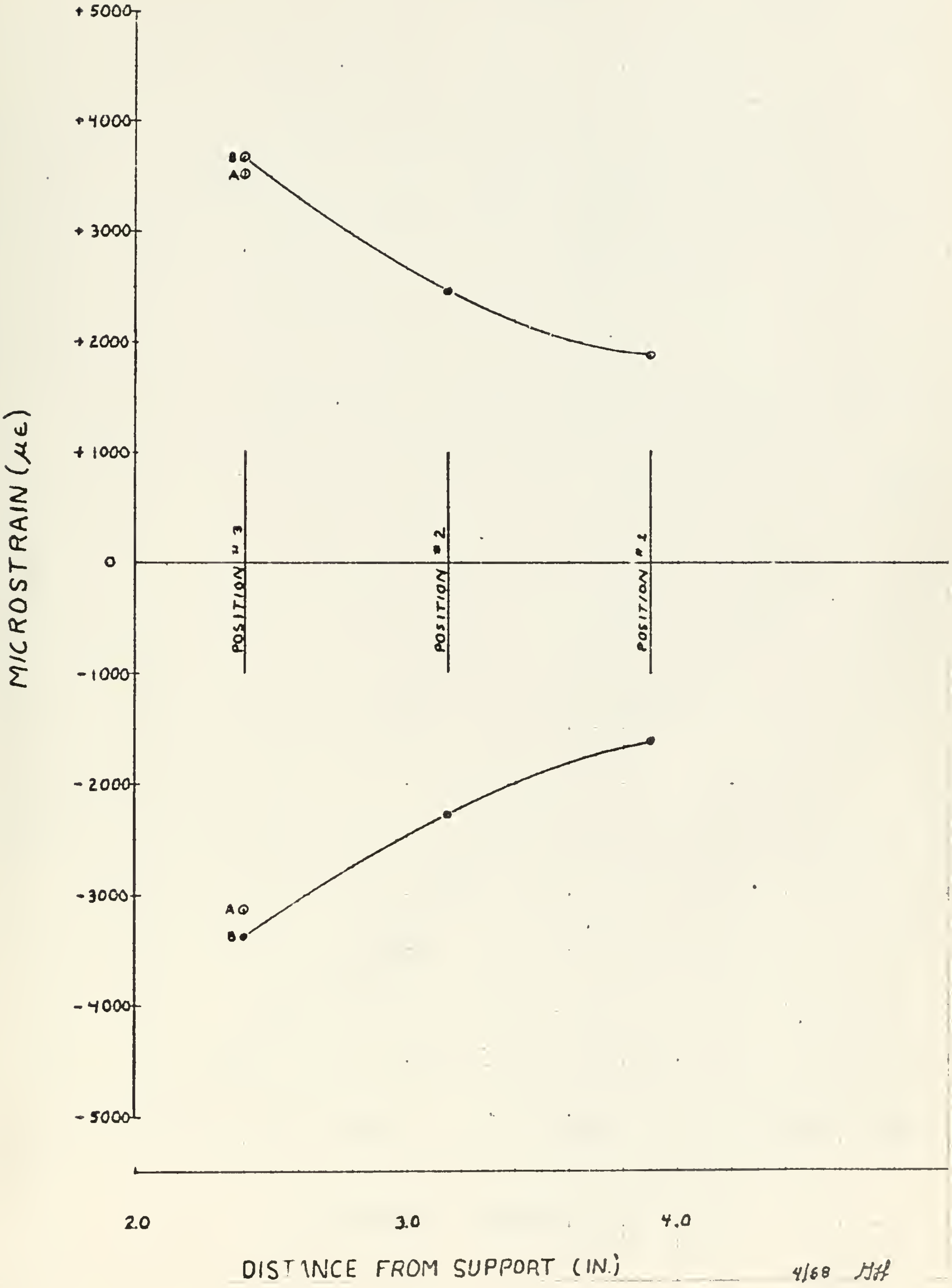
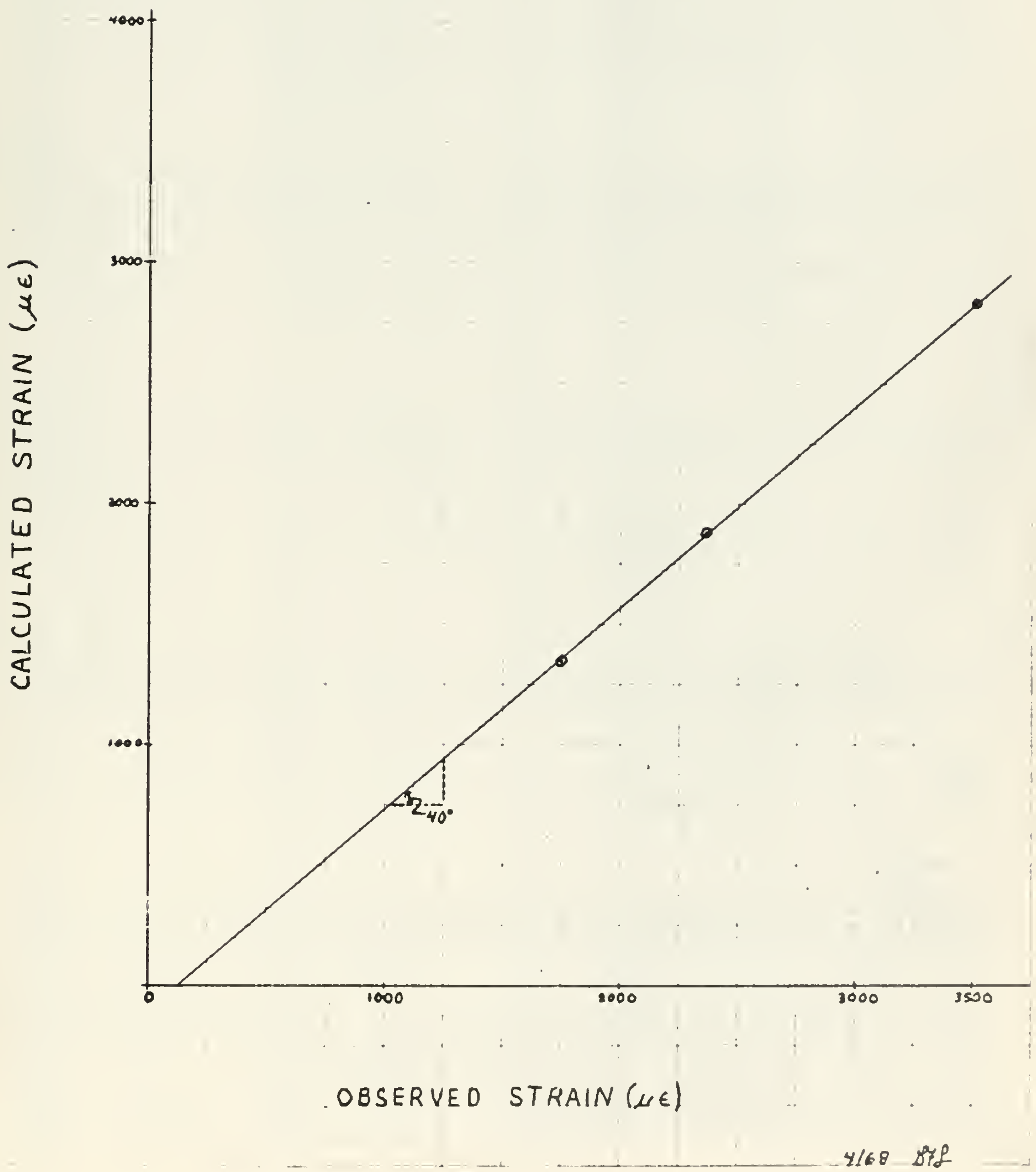


FIGURE III
COMPARISON OF CALCULATED VERSUS OBSERVED
STRAIN FOR FATIGUE MACHINE BLOCK POSITIONS



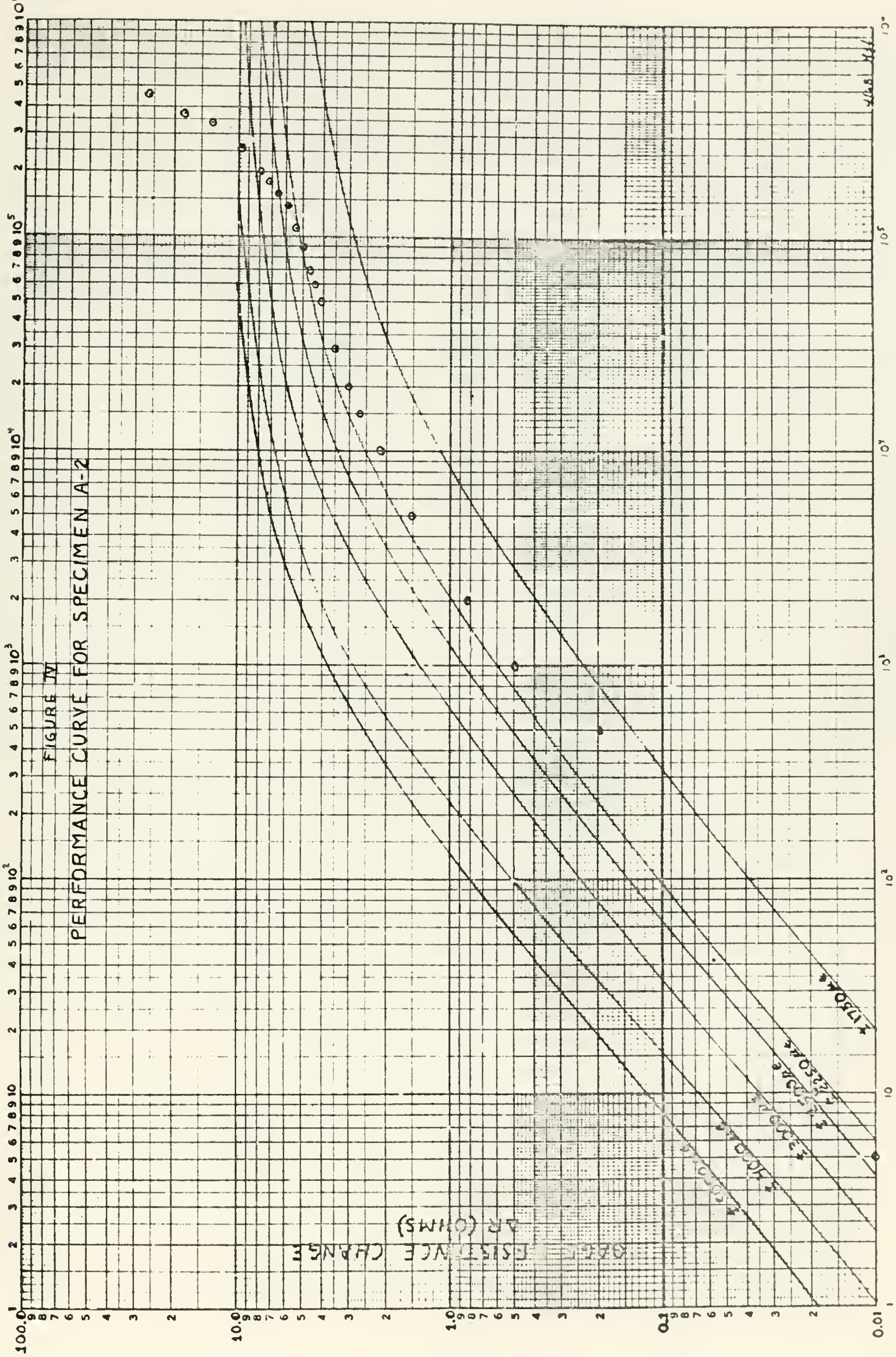


FIGURE IV
PERFORMANCE CURVE FOR SPECIMEN A-2
CYCLES
ΔR (OHMS)

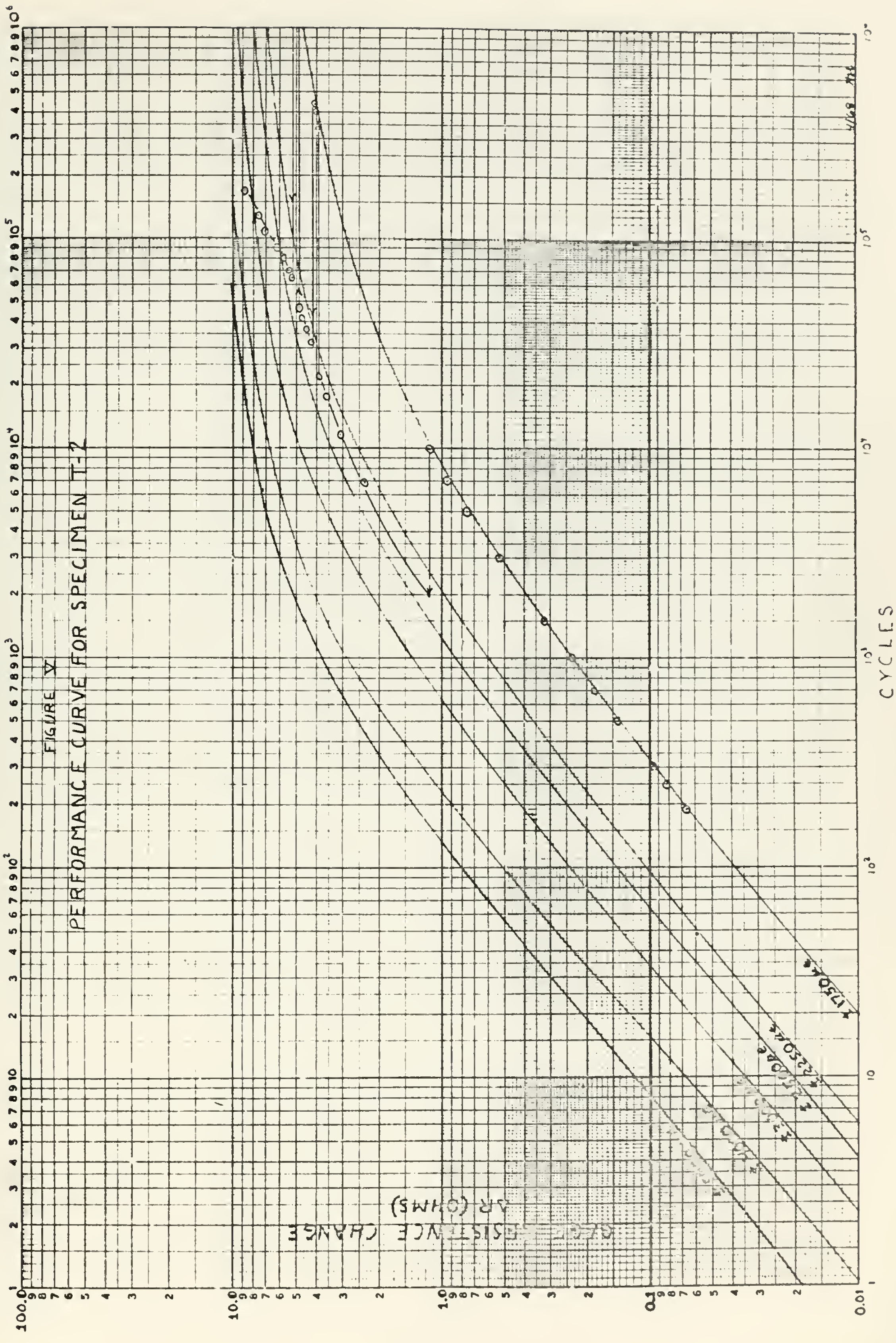


FIGURE V
PERFORMANCE CURVE FOR SPECIMEN T-2
CYCLES
ΔR (OHMS)

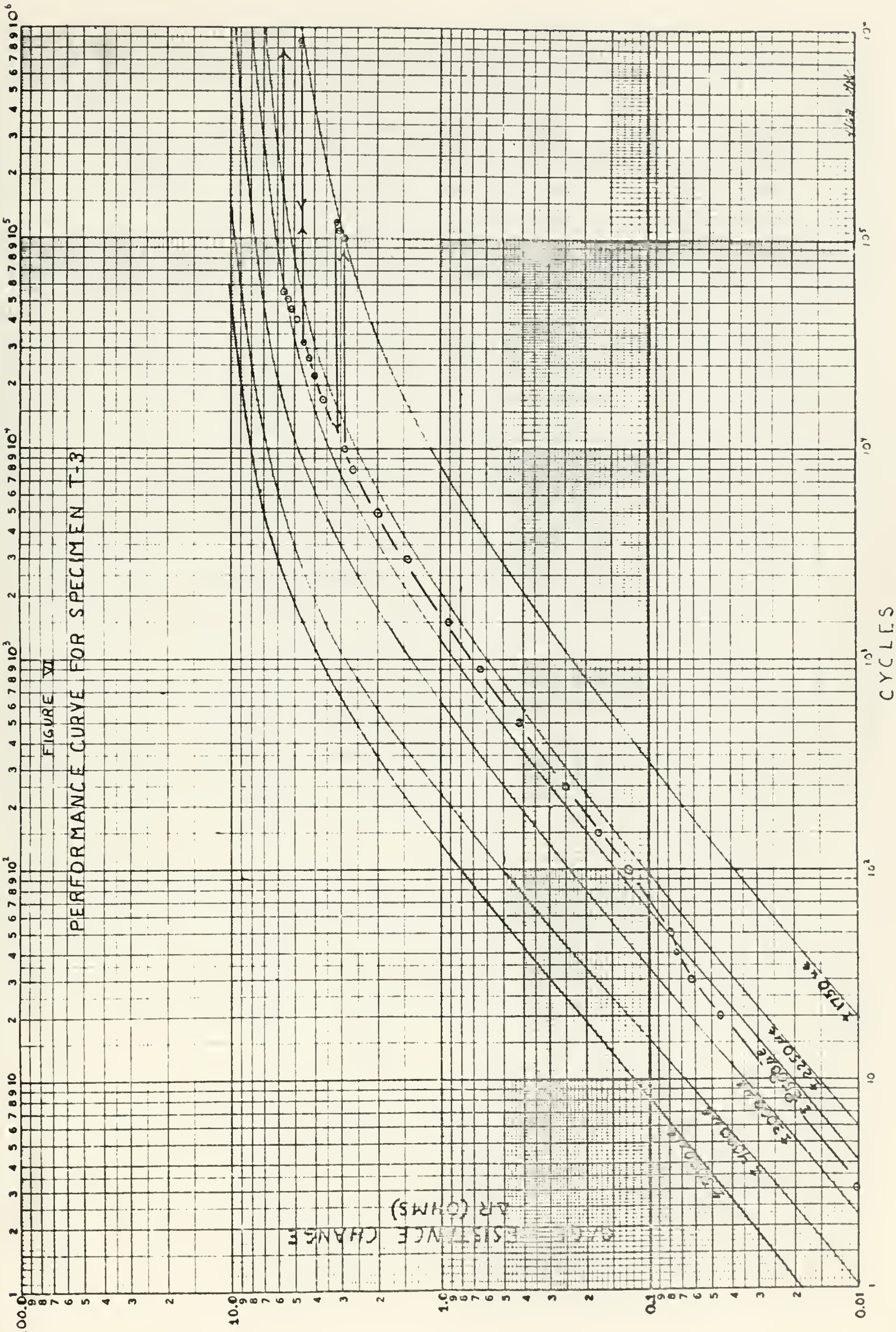


FIGURE VI
PERFORMANCE CURVE FOR SPECIMEN T-3
CYCLES
ΔR (OHMS)

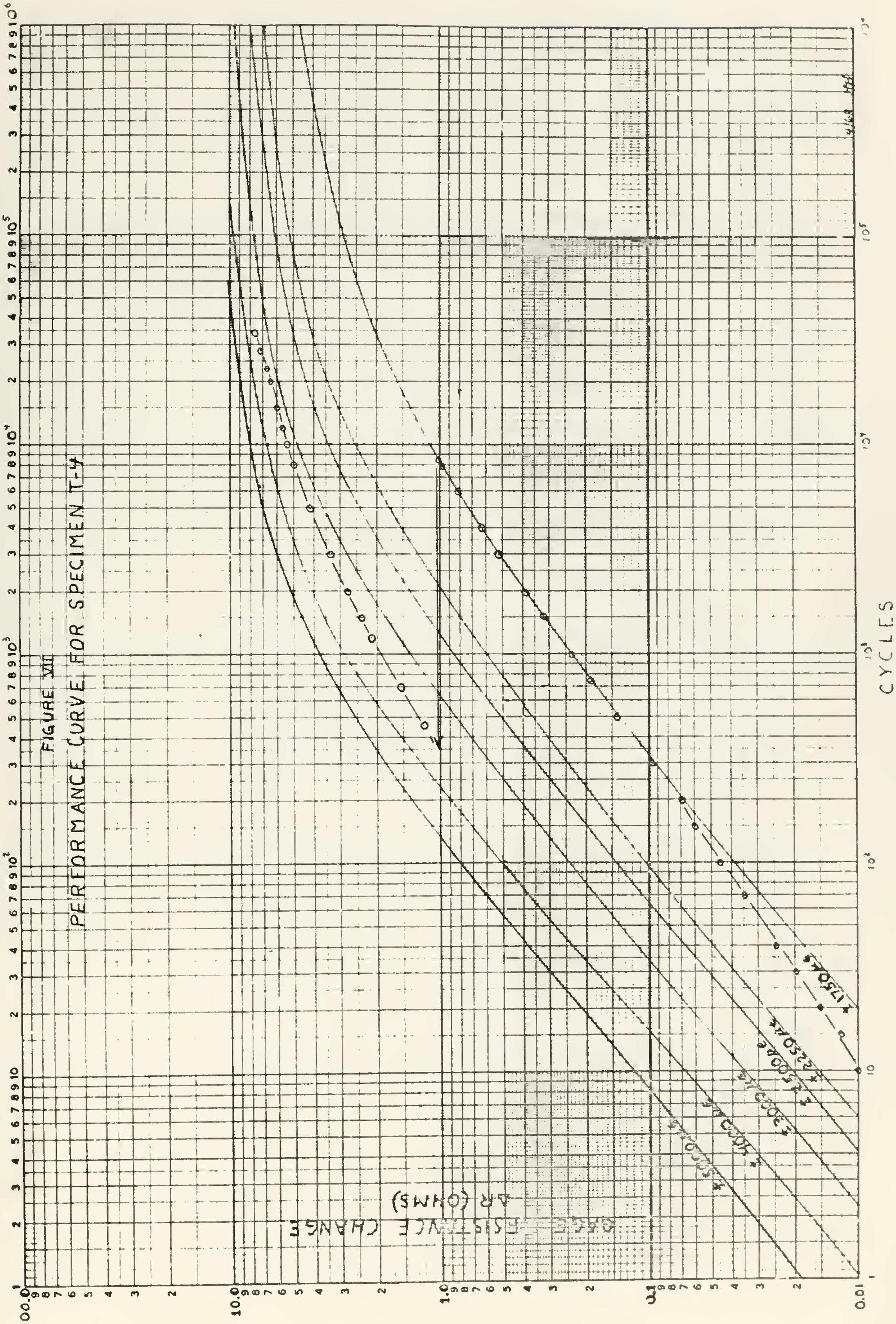


FIGURE VII
PERFORMANCE CURVE FOR SPECIMEN T-4

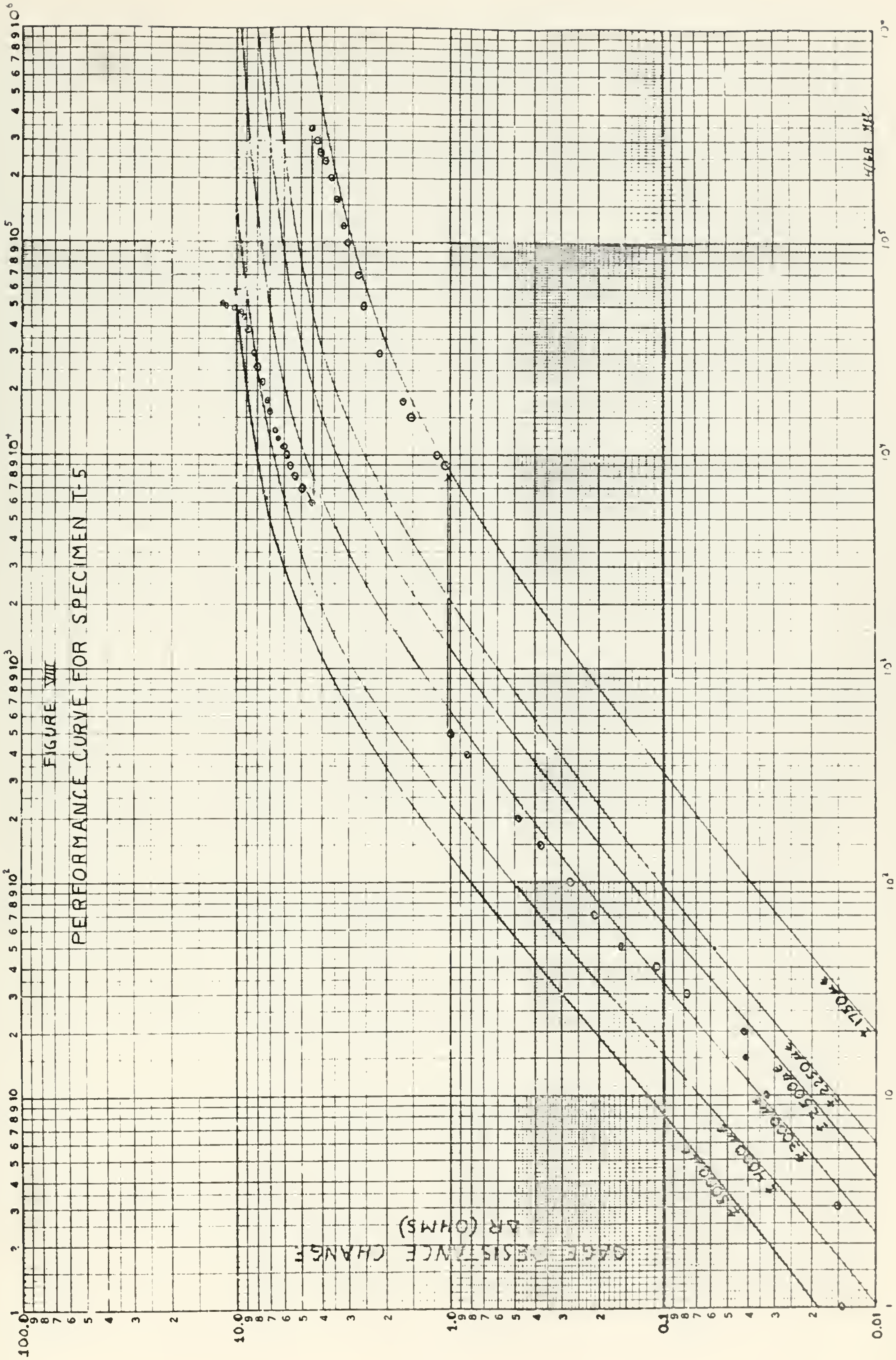


FIGURE VIII
PERFORMANCE CURVE FOR SPECIMEN T-5
CYCLES
GAGE RESISTANCE CHANGE
ΔR (OHMS)

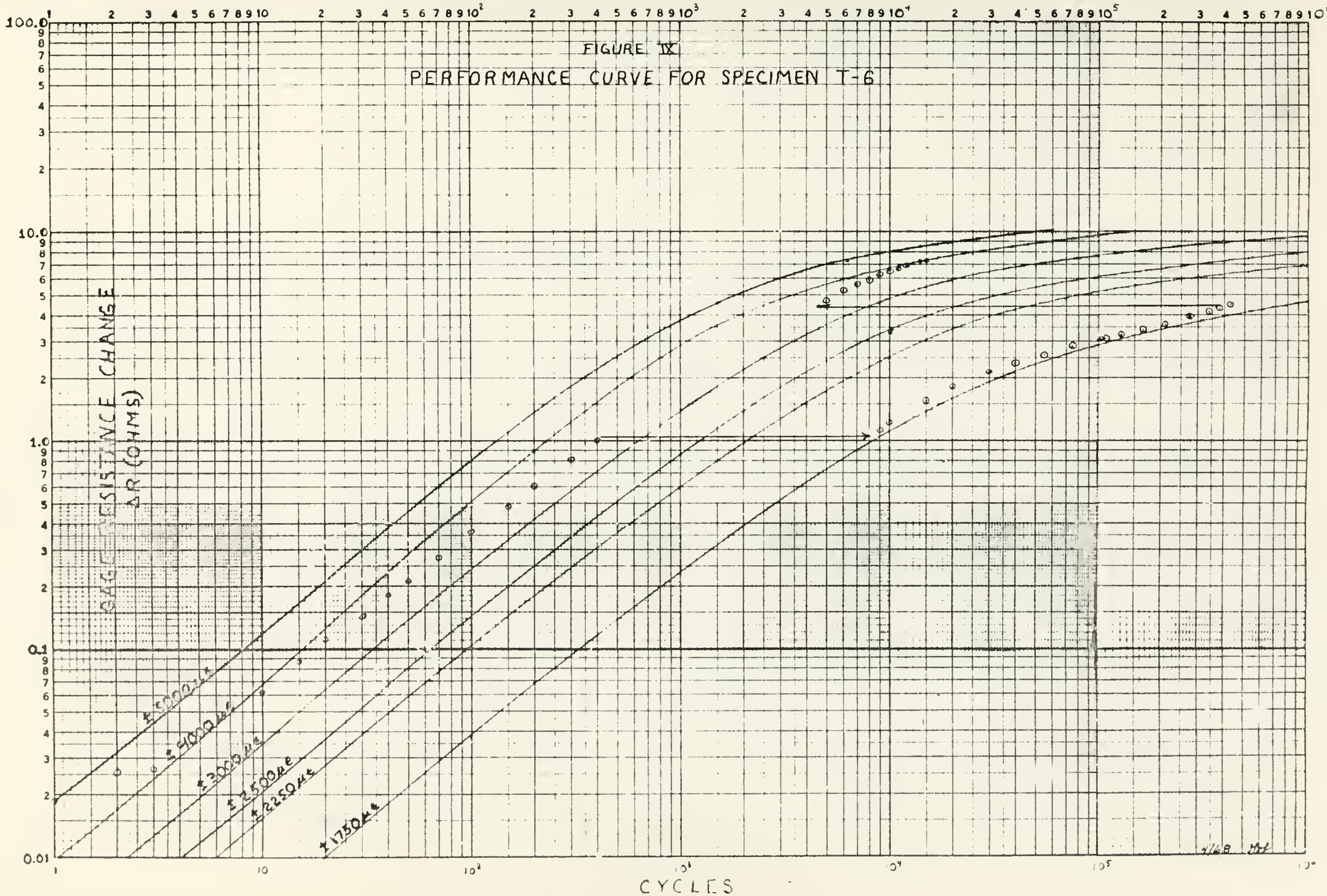


FIGURE IX
PERFORMANCE CURVE FOR SPECIMEN T-6

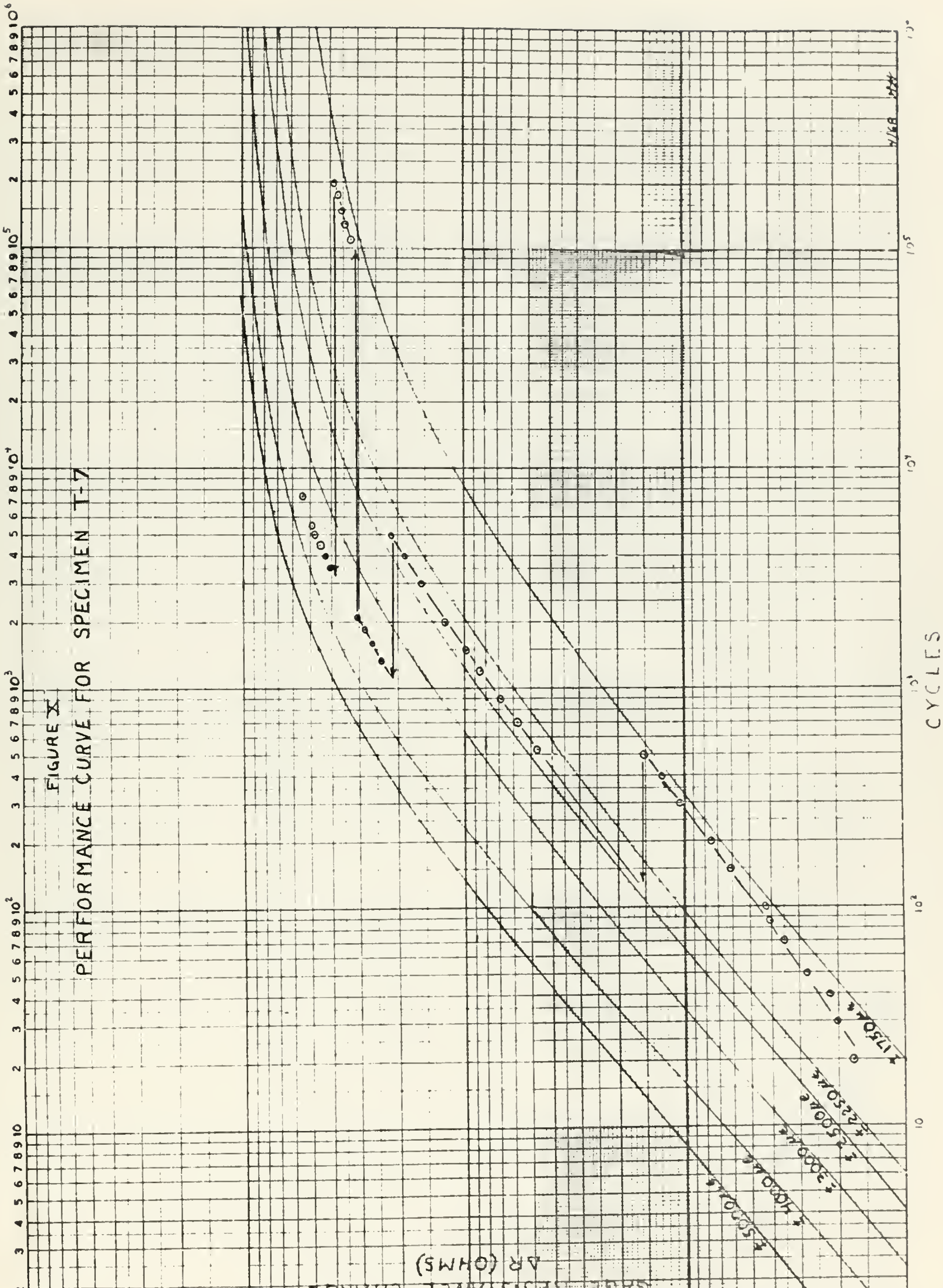


FIGURE X
PERFORMANCE CURVE FOR SPECIMEN T-7

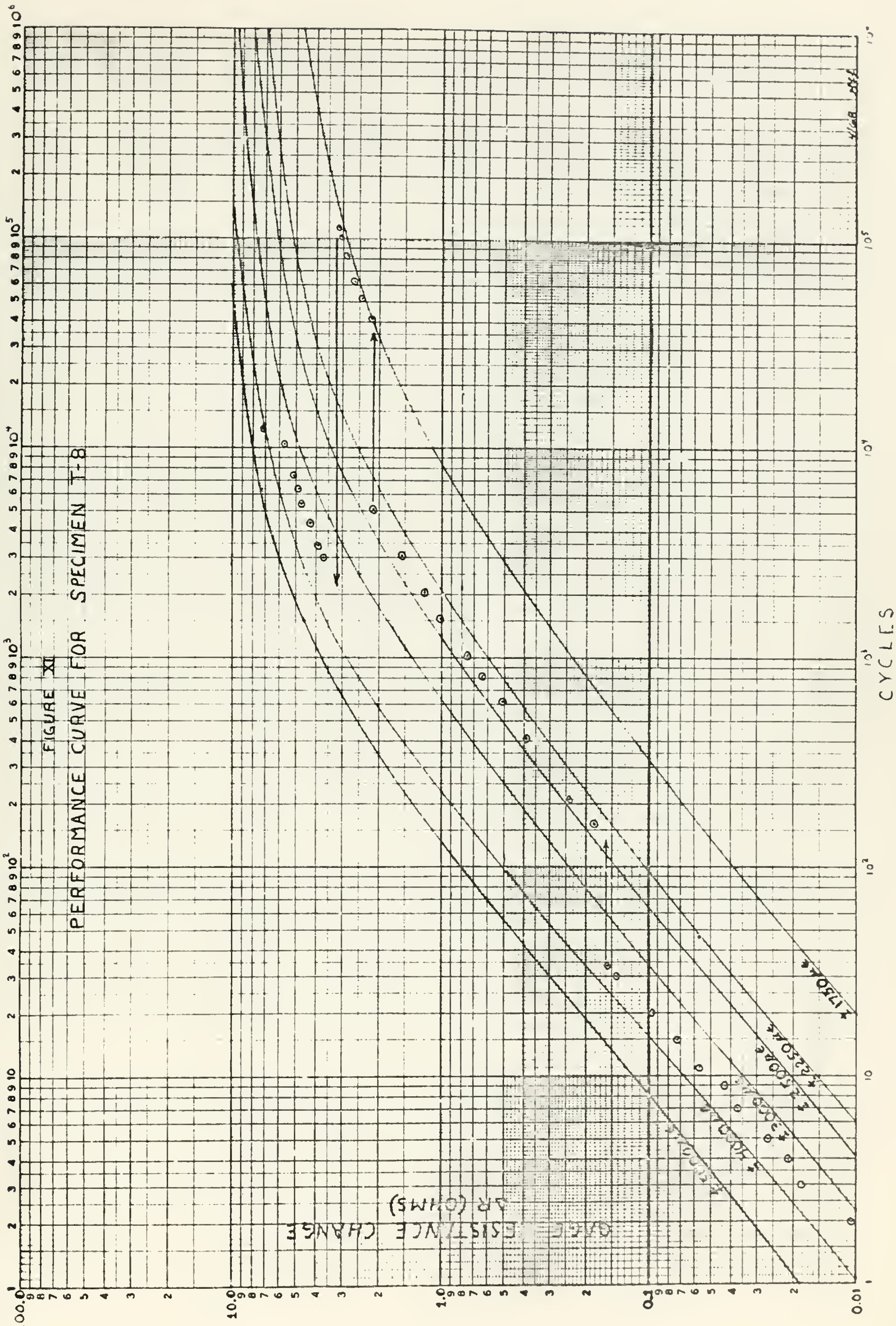
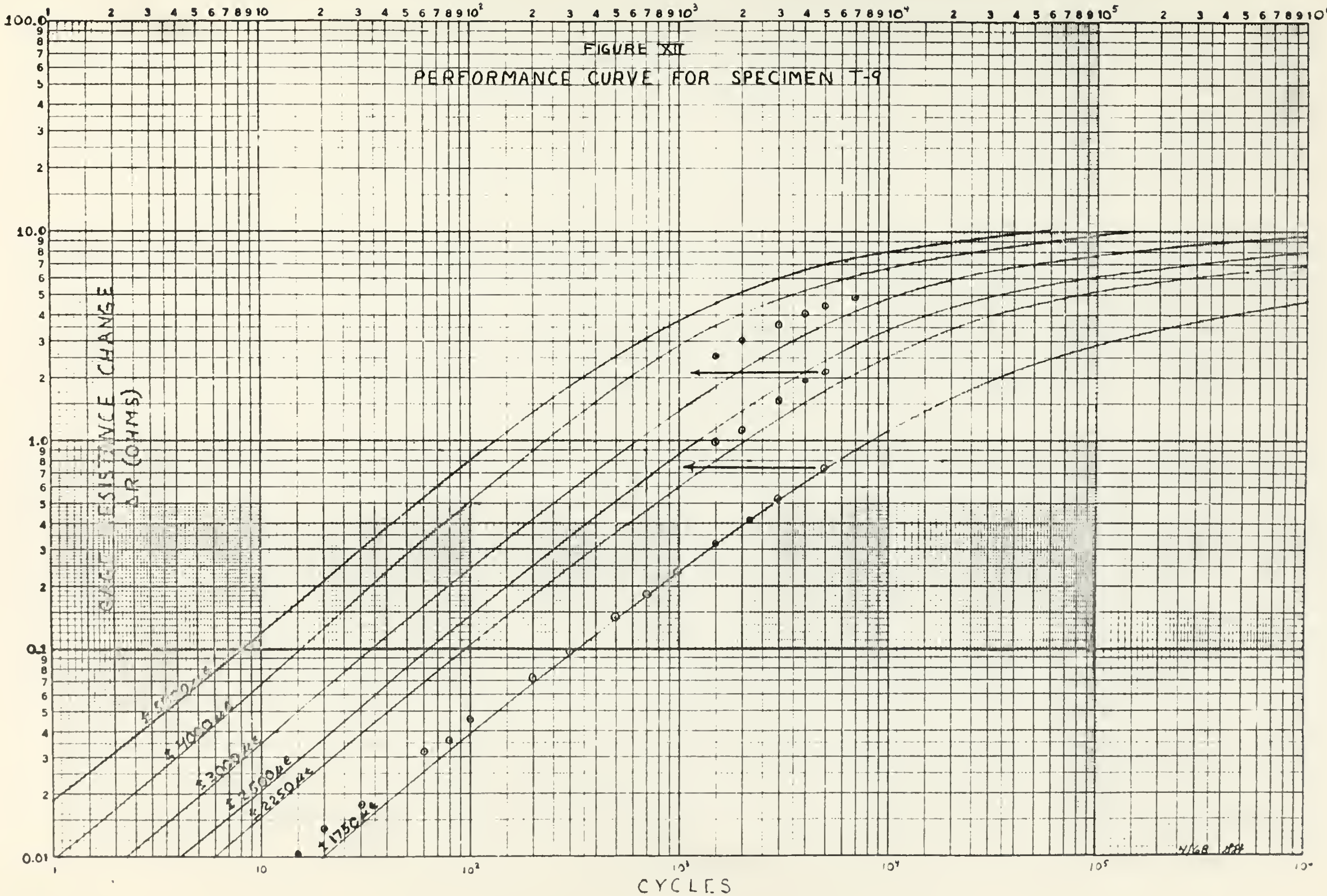


FIGURE XI
PERFORMANCE CURVE FOR SPECIMEN T-8

FIGURE XII

PERFORMANCE CURVE FOR SPECIMEN T-9



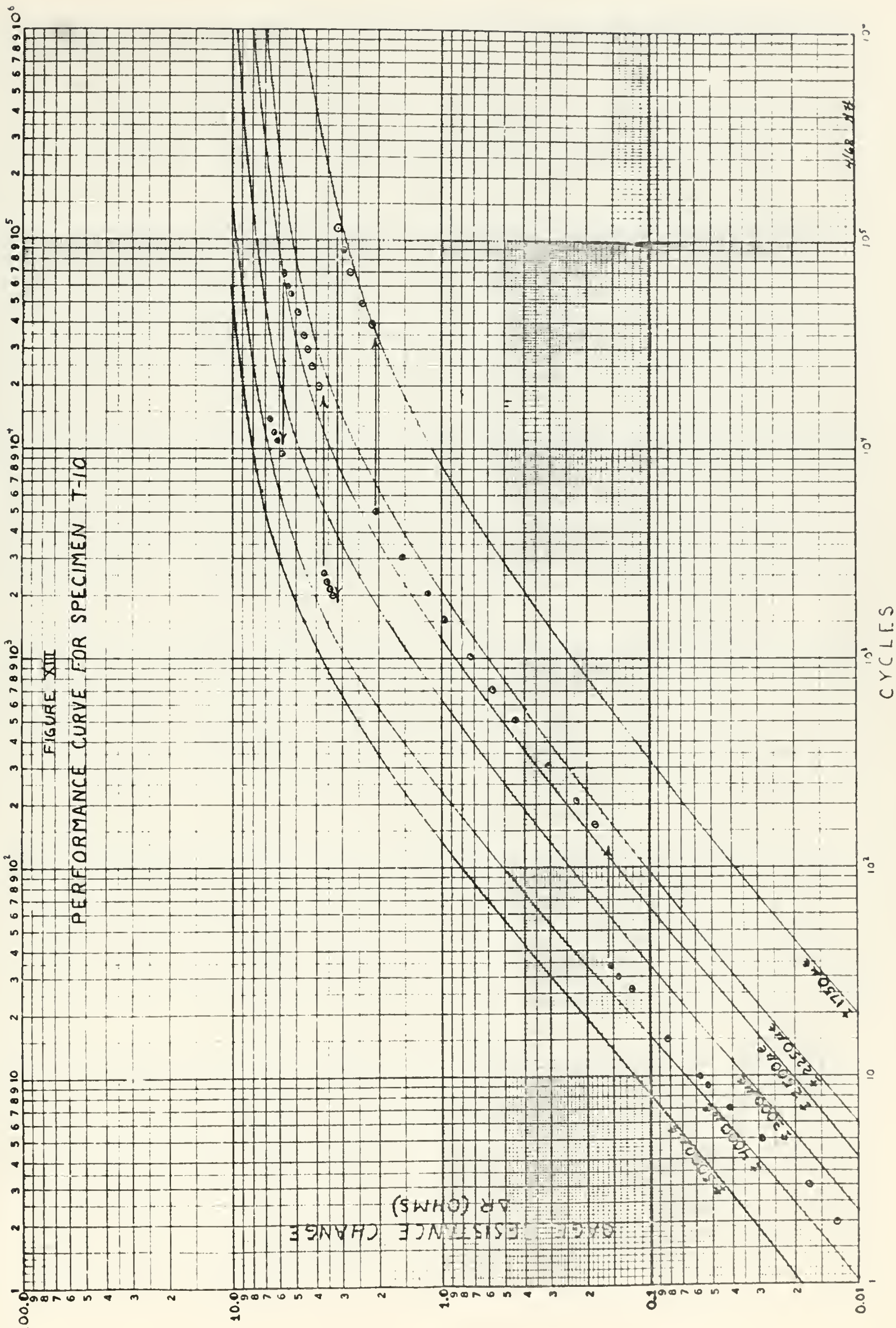


FIGURE XIII
PERFORMANCE CURVE FOR SPECIMEN T-10

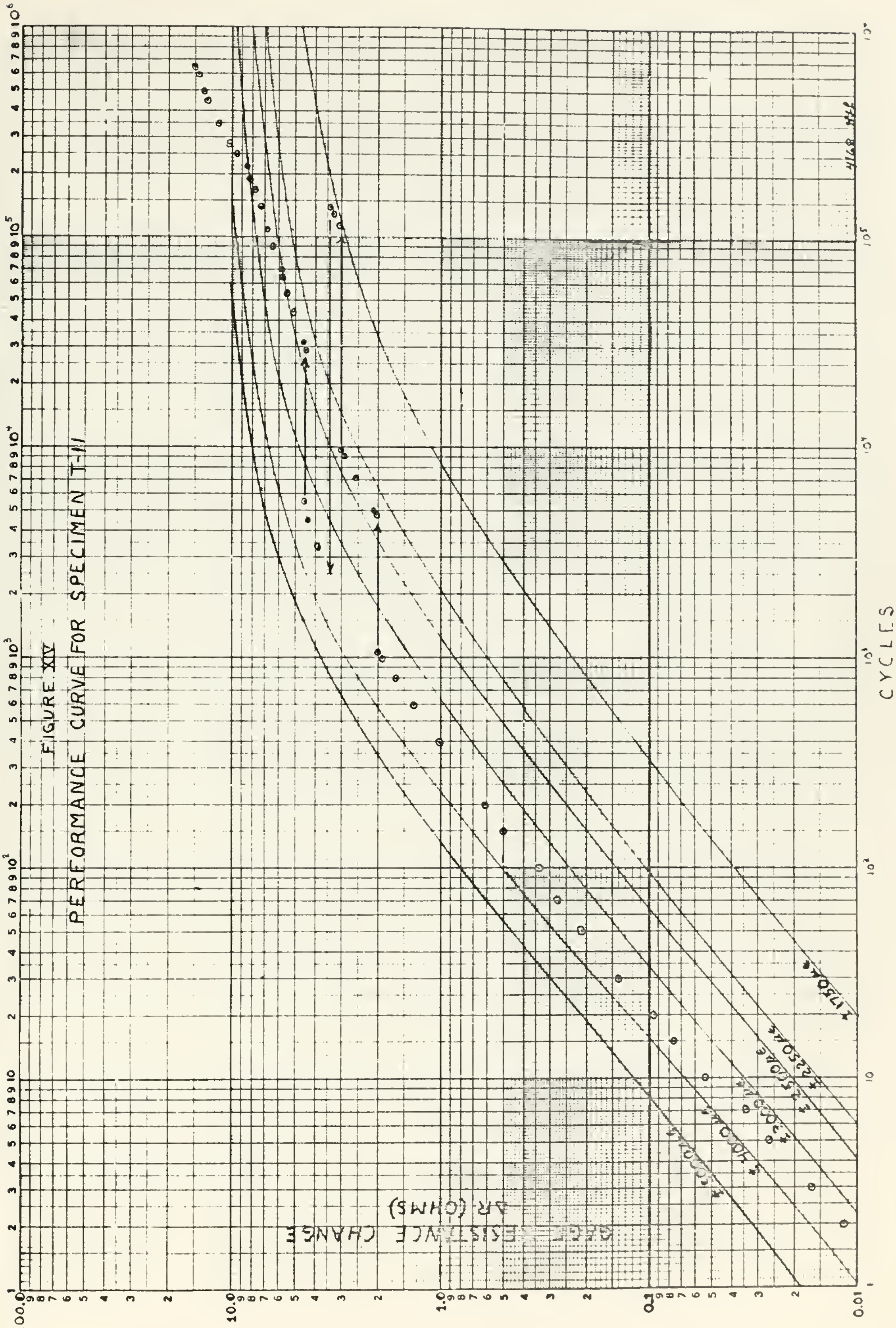


FIGURE XIV
PERFORMANCE CURVE FOR SPECIMEN T-11
CYCLES
ΔR (OHMS)

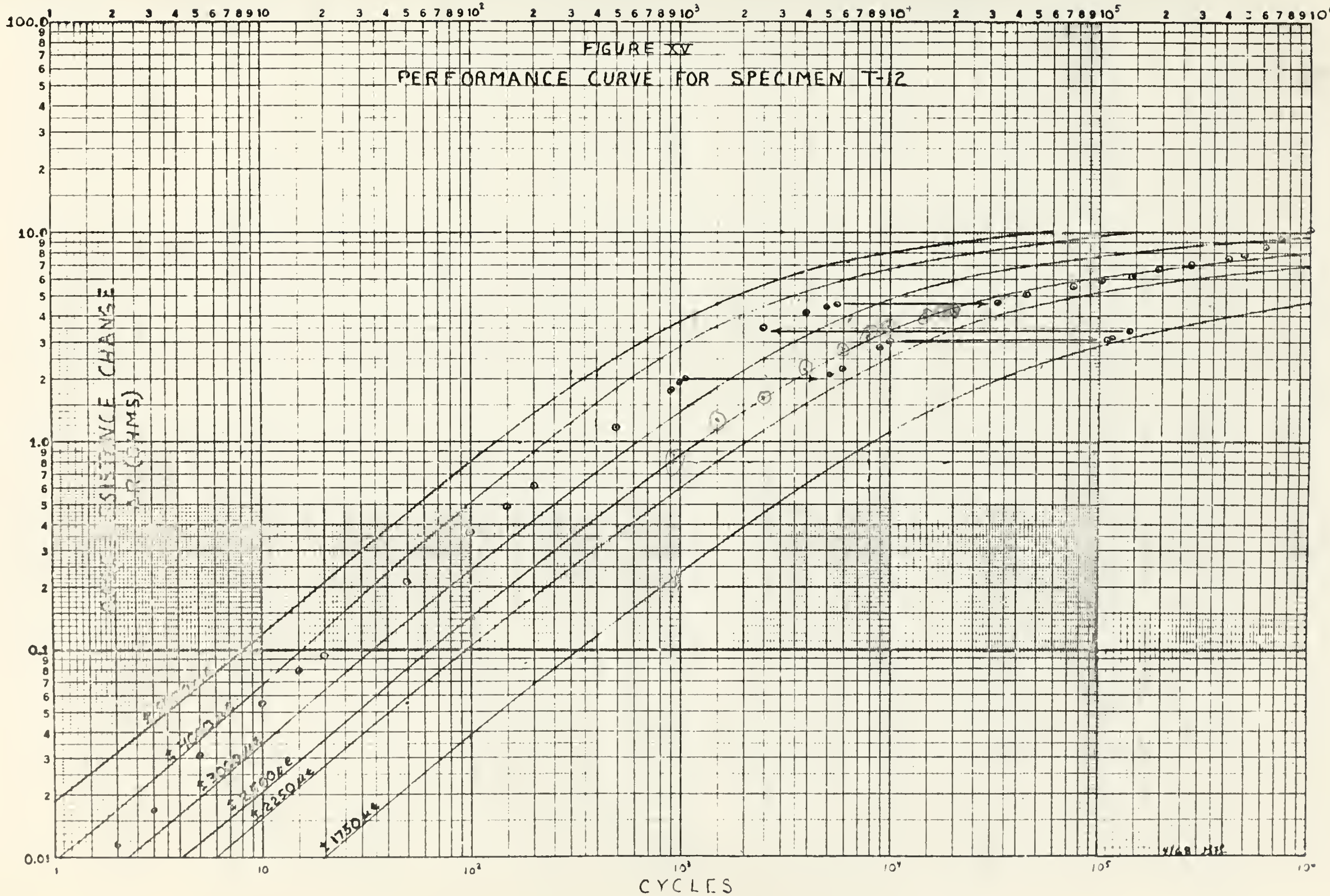


FIGURE XV
PERFORMANCE CURVE FOR SPECIMEN T-12

V. DISCUSSION OF RESULTS

TEST # 1: The results of position # 1 calibration for 0.250 inch aluminum are listed in Appendix D. The position of the spacer plate was such that true reverse bending was not occurring about the neutral unstrained position. This is evidenced by the tensile strain (+ 2975 $\mu\varepsilon$) being almost twice the compressive strain (- 1528 $\mu\varepsilon$).

The fact that true reverse bending is not occurring will in no way affect the results of test # 3, which will be conducted at the same strain level as determined in this test.

TEST # 2: The results of the block position calibration for a 0.175-inch titanium specimen can be seen in Figure II. The non-linearity of the tensile and compressive curves is attributed to the geometry of the test specimen. The specimen is non-uniform over approximately 15 percent of its width and height.

The tensile and compressive strains were of about equal magnitude. In this test the spacer plate was remachined and positioned to better approximate true reverse bending about zero strain. During this test the effect of clamp tightness on the average strain levels was checked. The variation in average strain for various nominal clamp tightnesses was 13 $\mu\varepsilon$. It was concluded that the average strain level in each block position would not appreciably vary with clamp tightness.

In clamping position # 3A the spring pushing the specimen against the cam bearing (Figure XXI) was not of sufficient stiffness to cause contact. The total deflection of the specimen was 0.19 inches vice 0.20 inches. A thin neoprene strip was placed between the spring and specimen. The specimen again deflected 0.20 inches and the position was designated # 3B.

The average cyclic strain values for each clamping block position are valid for 0.175 inch titanium alloy providing the dimensions in Table II of Appendix C are maintained.

<u>TEST # 3:</u> This test was conducted at the same average strain level throughout. The ΔR vs. N curve, Figure IV, was in close agreement with the manufacturer's performance data. At 160,000 cycles two small cracks appeared in the specimen. The test was continued to obtain gage performance data with a fatigue crack propagating.

The usefulness of data beyond 450,000 cycles was questionable and the test was terminated. Using graphical extrapolation techniques, the first specimen crack appears to have developed at about 125,000 cycles. Agreement between the test data and the S/N gage performance curves indicates that the S/N fatigue gage was properly bonded to the specimen and that the S/N fatigue machine was functioning properly. As a result of this verification test, the author considers his gage application technique to be of sufficient caliber to obtain accurate S/N gage performance data.

<u>TEST # 4:</u> Results of this test appear in Figure V. They are in exact agreement with the performance curves up to 70,000 cycles, which corresponds to $\Delta R = 4.9$ ohms. At this point the resistance change of the gage is increasing at too rapid a rate. At 90,000 cycles the strain level was increased by shifting the clamping block to position # 2. The ΔR vs. N curve continued to deviate from normal indicating gage or specimen failure. Under microscopic inspection no cracks were evident on the gage or specimen.

Between 70,000 and 90,000 cycles the specimen was in position # 1. The ΔR values were not plotted in Figure V because the extrapolated equivalent cycles corresponding to the shift in clamping block positions were greater than available performance data (10^6 cycles). The test was terminated at 200,000 cycles.

The S/N gage manufacturer's recommended evaluation technique was used exclusively after each average strain level change. The subsequent ΔR values plotted near the actual strain level.

<u>TEST # 5:</u> Results of this test appear in Figure VI. The graphical results of the cumulative cyclic fatigue are in close agreement with the performance curves up to 75,000 cycles ($\Delta R = 4.9$ ohms). The one exception to this occurs in early gage life (i.e., ΔR less than 0.075 ohms)

where the observed ΔR exceeds the expected ΔR by 40%. Beyond 75,000 cycles the gage and/or specimen appears to be failing because of the abnormal ΔR vs. N curve. Visual inspections of the gage and specimen did not reveal any fatigue cracks.

Although data was accumulated in position # 1, the ΔR vs. N values beyond 90,000 cycles were not plotted in Figure VI. As in test # 4, the equivalent cycles corresponding to position # 1 were greater than the available performance data. From this test it is apparent that the S/N gage evaluation technique for cumulative fatigue is accurate irrespective of the number of strain level shifts occurring.

<u>TEST # 6:</u> Results of this test appear in Figure VII. Once more in the early part of gage life (ΔR = 0.07 ohms) the observed ΔR exceeded the expected ΔR. Beyond 23,000 cycles (ΔR = 6.0 ohms) the gage and/or specimen appeared to be failing due to the abnormal ΔR vs. N curve.

At 48,040 one of the S/N fatigue gages solder tabs split thereby causing gage failure - see Figure XVI.

Except for the initial gage settling out period and the time after the gage fatigue crack had begun to propogate, the S/N gage accurately followed the manufacturer's performance data including the strain level shift.

<u>TEST # 7:</u> Results of this test appear in Figure VIII. Again in the early portion of gage life the gage ΔR appeared to be settling out. The gage resistance curve dipped below the expected ΔR level after the first 10 cycles. The erratic resistance readings continued until a gage resistance change of 0.15 ohms was attained. At 192,000 cycles (3.6 ohms) the resistance change curve began to deviate from normal. The Ti - 6Al - 4V specimen required well beyond 10^6 cycles in position # 3B to fail. Accordingly, all gage resistance upward deviations will subsequently be considered indicative of gage failure.

At 377,000 cycles a sharp increase in gage resistance occurred. After 5,000 additional cycles this increase was confirmed. The test was secured at 382,000 cycles with gage failure imminent. After settling out and before first indication of failure, the S/N gage performed in accordance with the manufacturer's predictions.

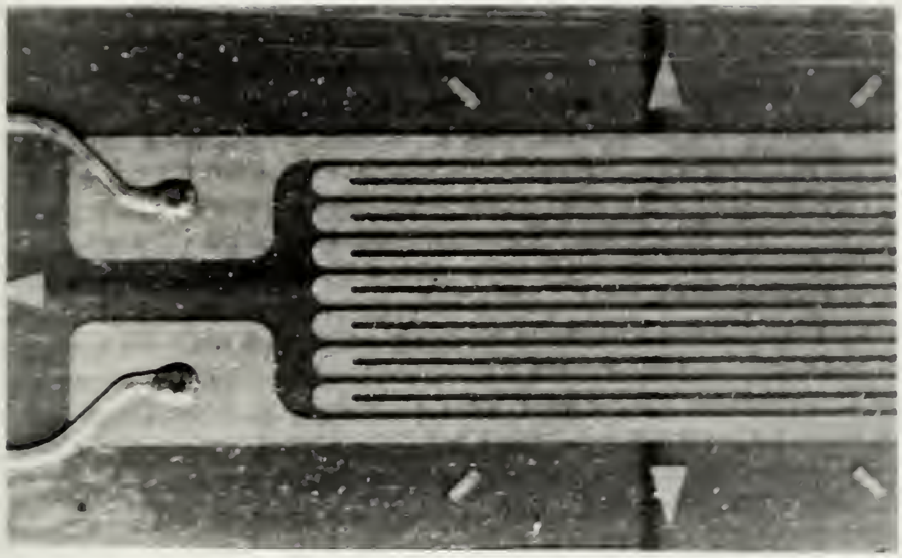


FIGURE XVI

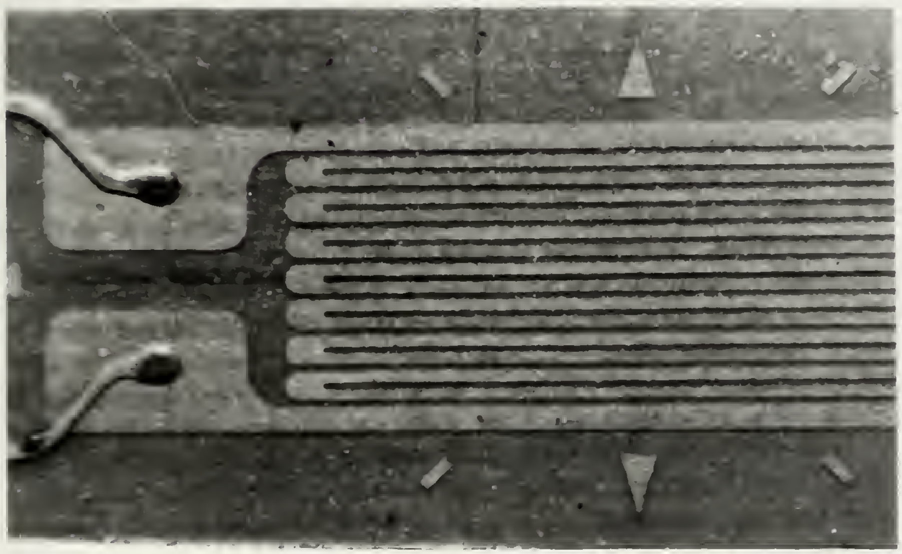


FIGURE XVII

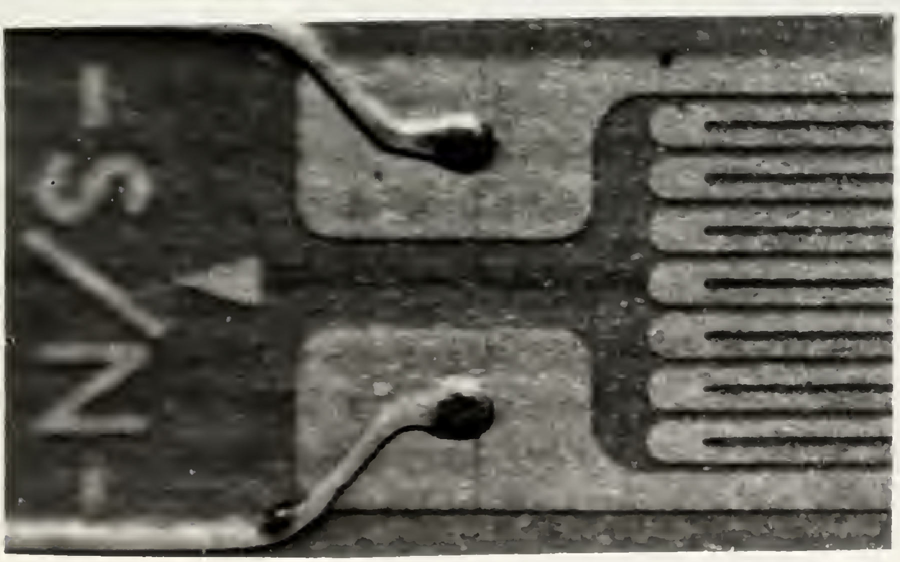


FIGURE XVIII

TEST # 8: Because the ΔR readings in the settling out period of test # 7 were so erratic, it was decided to conduct this test following the same format except for a slightly higher strain in position # 3. In Figure IX the gage resistance change readings are seen beginning to settle out at about 0.13 ohms. At approximately 212,000 cycles (3.65 ohms) the resistance change curve began to deviate from normal indicating the onset of fatigue failure.

At about 431,000 cycles both S/N fatigue gage solder tabs split as may be seen in Figures XVII and XVIII. Gage failure occurred very suddenly. Unlike test # 7 only one abnormal ΔR vs. N slope change was evident. In this test the strain level was changed after the initial indication of impending gage failure. After the increase in strain level, the abnormal gage resistance change still prevailed.

TESTS # 9 - # 12: All tests were similar in nature. Test results appear in Figures X - XIII. Based upon the S/N gage performance characteristic (Figure I) and the recommended cumulative fatigue technique (16), a number of strain level shifts were predicted for each test specimen. A tabulation of the predicted and actual results is given in Table I.

TABLE I

Test	Block Position	Cycles	ΔR (ohms) Predicted	ΔR (ohms) Actual
9	1	500	0.14	0.15
	2	4,880	2.10	2.14
	3B	1,000	3.05	3.05
	1	100,000	3.60	3.85
	3B	2,000	4.50	4.81
10	3B	34	0.14	0.16
	2	4,880	2.10	2.13
	1	77,000	3.05	3.17
11	1	5,000	0.75	0.74
	2	4,000	2.10	2.11

TABLE I (cont'd)

Test	Block Position	Cycles	ΔR (ohms) Predicted	Actual
12	3	34	0.14	0.15
	2	4,880	2.10	2.08
	1	77,000	3.05	3.16
	3	800	3.60	3.68
	2	38,000	5.00	5.27

In all tests there was observed an initial settling out period of gage resistance change similar to that in earlier tests. A ΔR value of 0.035 ohms was attained before the observed gage strain level was equal to the actual strain.

In tests # 9 and # 10 - # 11 there was no advance indication of gage failure. In test # 12 the initial indication of eventual gage failure using the slope - deviation method was at 115,000 cycles (ΔR = 5.0 ohms). In test # 9, one fatigue gage solder tab split between 111,000 and 113,000 cycles at 6.0 ohms. In test # 10, one fatigue gage solder tab cracked at 90,214 cycles at approximately 6.5 ohms. In test # 11, both gage solder tabs failed between 15,000 and 18,000 cycles at 5.5 ohms. In test # 12, both gage solder tabs failed between 140,214 and 142,214 cycles at about 7.0 ohms.

The variance between the predicted and actual gage resistance change is considered insignificant at all levels of gage life until failure. In addition there does not appear to be any relation between the number of gage solder tabs failing and either the order or magnitude of strain levels experienced.

<u>TESTS # 13 and # 14:</u> Results of these tests appear in Figures XIV and XV. A small perturbation in gage resistance values from the actual strain level is somewhat noticeable early in gage life. In test # 13 the ΔR values become predictable at about 0.045 ohms. In test # 14 the corresponding ΔR value is about 0.06 ohms.

The same test sequence was used in both tests in order to compare the observed data. The S/N gages used were from the same manufacturer's

lot grouping and they were applied to similar specimens in the same day. The temperature difference between tests was 1°F.

On a macroscopic scale the tests indicate that the gages accurately follow the manufacturer's performance data and evaluation technique for cumulative fatigue. In test # 13 the first deviation of ΔR from its expected value occurred at 41,500 cycles (ΔR = 4.8 ohms). No visible cracks were in evidence at this time. At 221,700 cycles (ΔR = 8.5 ohms) a crack partially across one tab of the gage appeared. The crack was located between the clamping block and the solder turret on the tab. At this time the gage resistance characteristic increased in slope again. The initial change in slope at 41,500 cycles appears to be caused by a weakening of the tab. In test # 14 the first deviation of ΔR from its expected track occurred at 60,000 cycles (ΔR = 5.2 ohms). At 565,000 cycles (ΔR = 8.0 ohms) a second and more noticeable increase in the slope of the gage resistance curve was noted. No cracks were observed in the specimen or gage. The test was continued beyond one million cycles until both tabs split at 1,330,000 cycles.

In both tests the resistance change characteristics were investigated on a microscopic scale before and after each decrease in average cyclic strain level. The data obtained in both tests regarding the apparent strain hardening phenomenon was almost identical. In each test a check made prior to every strain level shift revealed that the ΔR values for the gages were increasing normally. However, immediately after each strain level decrease a check of the resistance readings revealed that the gage resistance value had suddenly decreased.

The specific cycle count and ΔR values may be found in Appendix D. It is interesting to note from these tests that the ΔR values nominally decreased 0.02 ohms after each decrease in strain. The length of time (measured in fatigue cycles) during which the cumulative resistance was below its initial shift value varied from 55 to 1,100 cycles. The actual length of time during which the gage resistance was sub par increased in cycle number in direct proportion to the magnitude of ΔR.

In the third strain level shift of test # 13 from position # 3B to # 2, the gage remained for a period of 70 hours before being subjected to

further cyclic fatigue. A ΔR value decrease of 0.09 ohms vice the expected 0.02 ohms is attributed to a relaxation of the S/N gage's foil grid structure during the 70 hour delay period.

VI. CONCLUSIONS

The S/N fatigue gage is designed to be used as a recorder in the pre-crack formation period of a material's life. The fatigue gage monitors and maintains a permanent record of the total cumulative plastic strain energy in the outermost fiber of a material's surface. Under cyclic loading the performance of the gage is predictable when subjected to various constant strain loadings. It was found that the prediction of gage performance was valid regardless of:

1) the number of strain level changes;
2) the number of cycles at each strain level; and
3) the ΔR value at any one particular time.

If true gage performance is being monitored, it is best to use a material such as Ti - 6Al - 4V for the test specimen. Titanium alloys in the annealed condition are highly stable and have a good cyclic fatigue life as documented by Weinberg and Hanna (20); as such they will not interfere with the fatigue characteristics of the S/N fatigue gage. The spread in data obtained in the various tests is not considered excessive except in the area of ΔR at gage failure. The ΔR value at failure varied from 5.5 ohms to in excess of 60 ohms. The large readings of gage resistance at failure are attributed to the cracks forming in the gage tabs. All gage failures were observed occurring at the solder tabs which is not considered unusual since these tabs are the areas of highest stress concentration in the fatigue gage.

Throughout this investigation resistance-slope changes in excess of normal occurred well in advance of gage failure. These initial resistance-slope changes are indicative of gage failure. There is no specific slope on the log-log plot of ΔR vs. N which can be related to S/N gage failure. The log-log slope of a gage before failure is somewhat less than the typical slopes for most materials just before they fail. Once the fatigue gage reaches the point in its life where

this greater than normal resistance-slope changes occurs, the usefulness of the gage is questionable. The observed values of ΔR at which these first changes occurred were from 3.6 - 6.0 ohms in 8 out of 11 tests. In the other three tests there was no resistance - slope change prior to failure.

In the course of this investigation it was noticed that there was a perceptible decrease in S/N fatigue gage resistance after the gage had been subjected to any measurable rest period (i.e., greater than 12 hours). This decrease may be partially attributed to: a cooling of the fatigue gage foil grid after being subjected to high frequency cycling; and to a strain relaxation of the grid foil as hypothesized by Horne (6). The amount of decrease was never in excess of 0.04 ohms and was therefore not considered too relevant to the overall results.

When mounted on the relatively stable titanium base metal, the S/N fatigue life gage definitely exhibits a short-lived decrease in resistance immediately after a decrease in strain level. This decrease in ΔR is believed to be caused by the work/strain - hardening process noted in 1955 by Rally and Sinclair (15).

VII. RECOMMENDATIONS

The S/N fatigue gage should be used in conjunction with the various proposed procedures of predicting cumulative fatigue crack initiation.

The decrease in S/N gage resistance referred to me by Whitehead (13) exists when the gage is mounted on a Ti - 6Al - 4V specimen. This phenomenon should be further investigated with other types of materials to classify and determine what effect this decrease in ΔR has on the overall gage performance.

Johnson (8) found that the ΔR of two S/N gages mounted by Triebes (19) on a 2024-T4 aluminum flat bar had apparently increased in a 12 month period. In an attempt to resolve this discrepancy, three S/N fatigue life gages have been mounted on separate 2024-T4 aluminum specimens with their respective ΔR values recorded. It is recommended that the resistance of these three gages be periodically checked to determine the effect of shelf life on the S/N gage.

The S/N fatigue has now been on the market since late 1965. Since that time an exhaustive and comprehensive evaluation of the gage has been in progress. The time for extensive application of the S/N gage is now at hand. The S/N fatigue gage should be installed on those primary structures designed for an infinite life whenever the fatigue strength of a component is in doubt. It also should be installed on components whose hydrodynamic, aerodynamic or other weight limitations have necessitated a limited life design, to indicate when the component should be replaced.

VIII. APPENDIX

A. PREPARATION OF REVERSE BENDING SPECIMENS

The W.T. Bean S/N notched fatigue specimen was chosen as the prototype specimen geometry for the following reasons:

1. The specimen was designed for use with the W.T. Bean portable S/N fatigue machine (see Appendix B for a description of the S/N fatigue machine);

2. The manufacturer's predicted gage performance curves were based upon this specimen geometry;

3. The specimen was of sufficient size to conveniently mount one S/N fatigue gage;

4. The geometry insured a known stress concentration opposite the notched portion of the specimen.

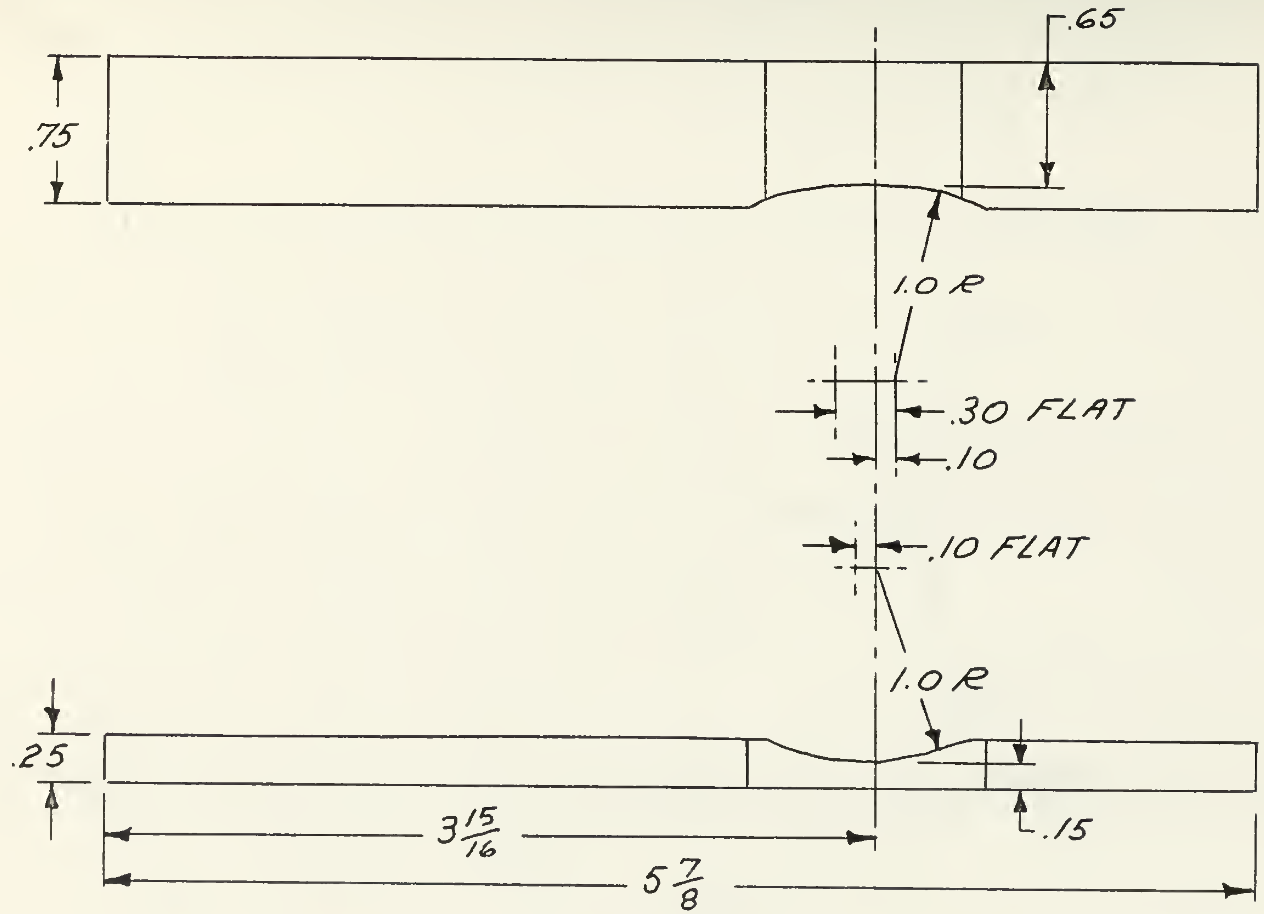
The reverse bending specimens were fabricated from 2024-T4 aluminum and Ti - 6Al - 4V titanium alloy. The 2024-T4 specimen geometry is shown in Figure XIX. The Ti - 6Al - 4V specimen geometry is shown in Figure XX. The nonavailability of 0.250" titanium alloy and subsequent substitution of 0.175" titanium alloy sheet necessitated the minor deviation in specimen types. The difference between the two specimen types are as follows:

1. The Ti - 6Al - 4V specimen was shortened 0.3" to permit its use in clamping block position # 3;
2. The Ti - 6Al - 4V specimen's vertical dimensions were scaled in accordance with the ratio of aluminum to titanium specimen thickness (i.e., 0.175/0.250).

All specimens were checked after preparation to ensure that there were no large scratches or pits and that all final polishing marks were parallel to the specimen axis.

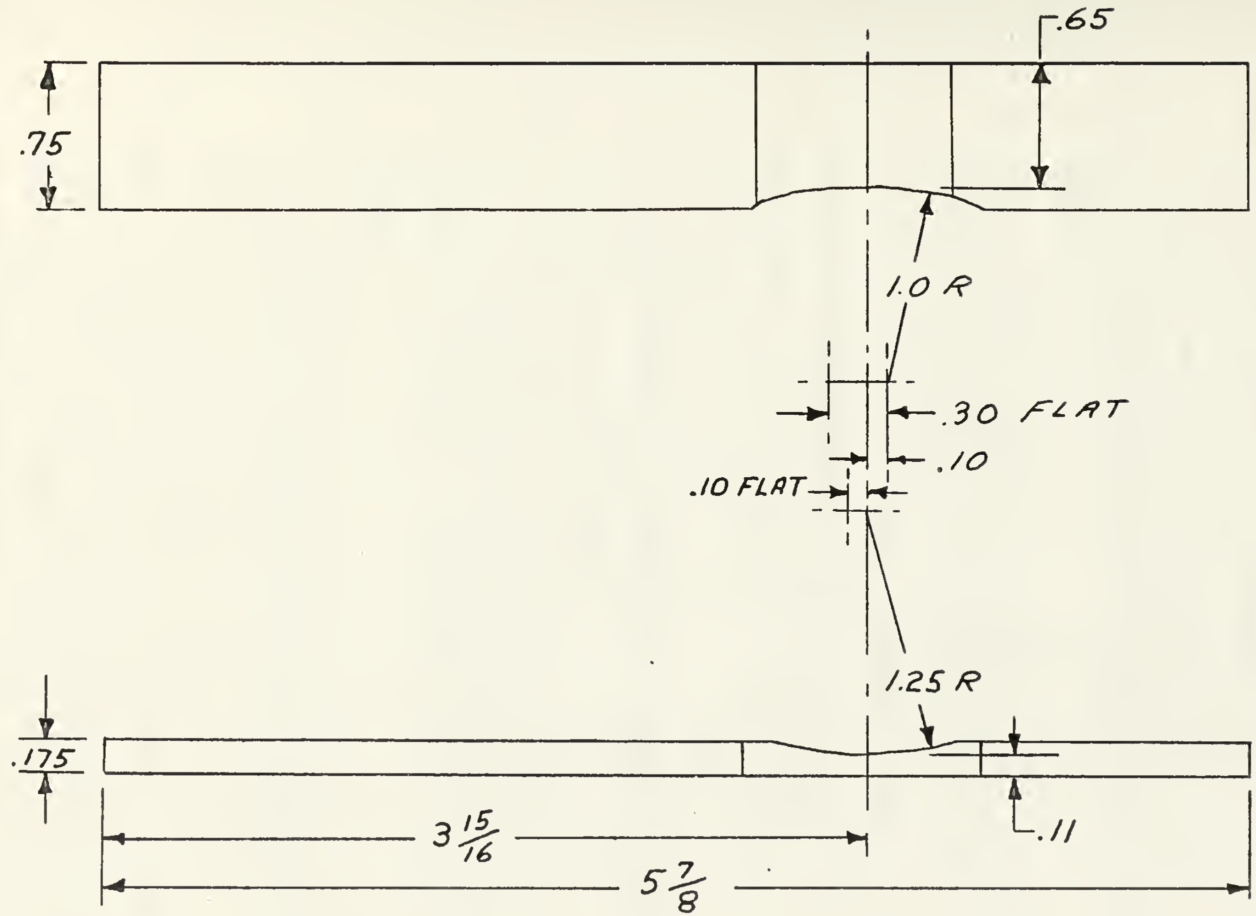
One S/N fatigue life gage was mounted on the flat surface of each specimen. The gage centerline was at a distance of 0.05" from the center

FIGURE XIX



S/N-FATIGUE SPECIMEN-TYPE NO. 1

FIGURE XX



S/N-FATIGUE SPECIMEN-TYPE NO. 2

of the notched section with the fatigue gage solder tabs facing the clamped end of the specimen.

The procedures specified by W.T. Bean (16) and (17) which were followed in the preparation of the specimen's surface and in gage installation in their order of accomplishment was as follows:

1. clean specimen surface with gauze pad saturated with Acetone;
2. be sure surface is dry and at a temperature between 70°F and 100°F;
3. dip one-inch strip of No. 400 grit paper into Metal Conditioner, lap surface, and remove residue with a clean tissue;
4. repeat 3 and indicate gage location, using a 8-H pencil;
5. apply Metal Conditioner to specimen surface with cotton swab and remove with one stroke of clean tissue;
6. wash hands;
7. apply Neutralizer to surface with cotton swab and remove with one stroke of clean tissue;
8. lap bonding surface of gage with a circular motion on a glass plate, using finger to apply light uniform pressure to top surface of the gage - fine pumice powder was used as the lapping powder;
9. place gage, face up, on clean surface and, for gages without attached leads, position the terminal strip at the end of the gage;
10. apply cellophane tape over top of gage (and terminal strip);
11. carefully lift gage assembly from working surface and clean back of gage (and terminal) with cotton applicator slightly moistened with Neutralizer;
12. place gage in position on specimen;
13. starting at one end of the cellophane tape lift gage assembly, leaving other end of tape attached to the specimen;
14. apply thin film of Blue 910 Catalyst to back of gage (and ter-

minal strip) and allow to dry - approximately 1 minute;

15. apply two drops of 910 Adhesive to gage area of specimen;
16. feed gage and tape onto surface, holding free end of tape above surface with one hand and using ball of tissue in other hand to quickly force gage assembly into place with one stroke;
17. within one second press gage firmly into contact with surface using thumb or finger; maintain pressure for approximately thirty seconds;
18. wait at least two minutes before removing cellophane tape from top of gage (and terminal);
19. set powerstat voltage at 98 VAC for a 22.5 watt soldering iron with a 1/16-inch conical tip;
20. tin terminal strip and ends of attached gage leads with rosen-core 63-37 tin-bed (Bean 300°F) solder;
21. place masking tape over gage face to prevent any loose solder beads from burning and possibly damaging the gage;
22. form the two single gage leads into a "C" shape to insure adequate slack between the gage and the terminal strip;
23. place 300°F solder on top of the gage lead which is positioned on the terminal strip;
24. bring the soldering iron down over all three items and hold for two seconds while continually feeding solder; remove solder and then lift the iron;
25. float masking tape loose with rosin solvent and remove all solder flux from terminal strip.

Specimens serial number A-1 and T-1 were used for clamping block position calibration. Strain gages were mounted on these specimens in lieu of S/N fatigue gages. The strain gages were mounted using procedures similar to those outlined above except that lapping was not required and leads had to be attached to gage. A terminal strip was placed on the top, forward edge of the clamping block as may be seen in Figures XXI and XXII. All specimen fatigue gages were connected to this terminal strip with sufficient

slack in the lead wire to minimize the possibility of fatigue failure in the electrical connection as recommended by the manufacturer (16).

The initial resistance of each gage was measured by a wheat-stone bridge. A strain indicator balance check was conducted to insure that the initial gage readings were mid-scale on the indicator. The readings were then checked for any drift which would be considered as evidence of a poor bond. If all these preliminary checks were satis-factory, the preparation of the specimen was considered complete.

FIGURE XXI

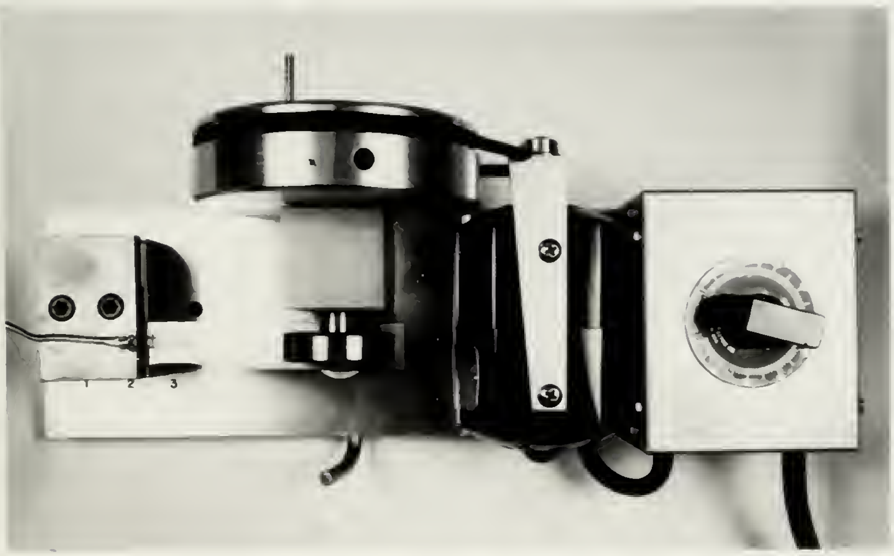


FIGURE XXII

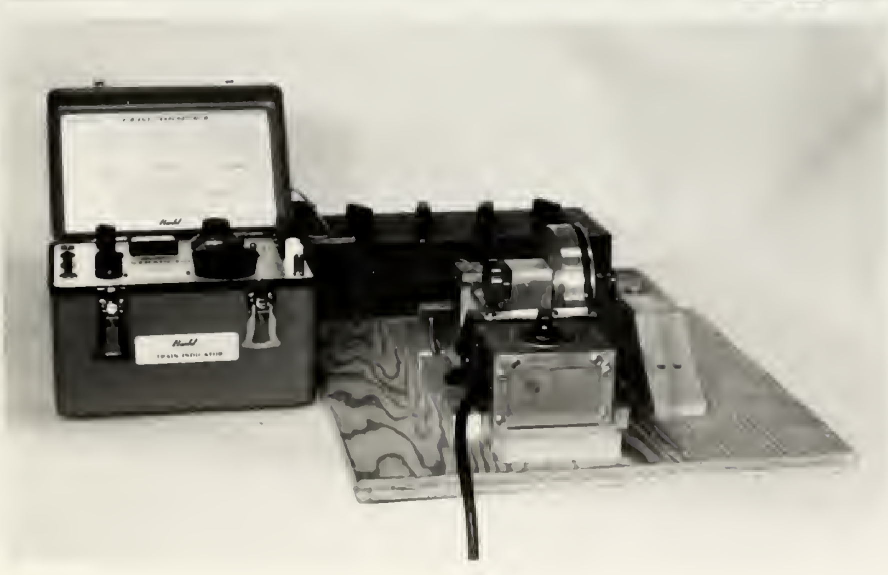


FIGURE XXIII

B. DESCRIPTION OF APPARATUS

S/N FATIGUE MACHINE

All fatigue tests were run on the W.T. Bean S/N fatigue machine as shown in Figures XXI and XXII. This same machine was utilized in the formation of the manufacturer's predicted gage characteristics. It was therefore deemed prudent that the same type fatigue testing machine be used to provide more meaningful gage performance data.

The machine is a variable speed, constant displacement device for low-cycle fatigue studies. The machine may provide a number of different strain levels by varying the position of the clamping block (i.e., approximately 1700$\mu\varepsilon$ - 5000 $\mu\varepsilon$). The thickness of the specimen being tested will also vary the strain level at each different position of the clamping block. A specimen may be tested in reverse bending, all tension or all compression depending upon the position of the shim plate in the clamping block and the attitude of the gage on the specimen.

Various methods may be used to determine the speed and actual number of revolutions of the fly-wheel. The fly-wheel drives a ball bearing eccentric which cycles the specimen. A strobe light focused on a white diametrical line on the fly-wheel may be used, however the accuracy of cycle count was not considered within acceptable tolerances.

In order to obtain a true count of fly-wheel rotation, the machine was slightly modified. A steel pin was tapped and mounted off-center on the fly-wheel. The pin was used to turn a 5 digit mechanical counter which was mounted separately to the S/N fatigue machine - see Figure XXIII.

BUDD PORTABLE DIGITAL STRAIN INDICATOR:

The Budd Model P-350 was used to measure all resistance changes (ΔR) and strain levels. The P-350 is a true quarter bridge instrument, incorporating both 120 and 350 ohm dummies. It has jack accomodations for full, half and quarter bridge external circuits. The instrument has a

range of ± 50,000 $\mu\varepsilon$ with a variable sensitivity and built-in zero balance control feature. The indicator may be used with strain/fatigue gages having resistances which vary between 50 to 2000 ohms and gage factors between 0.10 and 10.00. The Budd Model P-350 has a gage readability of 1 $\mu\varepsilon$ and an accuracy of ± 0.1% of reading or 5 $\mu\varepsilon$, whichever is greater.

DECADE RESISTANCE BOX

A General Radio Company, Type 602-N, decade resistance box was utilized in a half-bridge circuit while measuring all fatigue and strain levels. The instrument has a range of 0 - 11,111 ohms with an accuracy of ± 0.05%.

FAE STRAIN GAGE

The FAE strain gage is a SR-4 epoxy foil general purpose strain gage (3). The following information is applicable to the FAE strain gage used:

Manufacturer: BLH Electronics, Inc.
Type: FAE - 25 - 12S13
Gage Resistance: 120.0 ± 0.2 ohms
Gage Factor: 2.04 ± 0.5%
Overall Gage Length: 0.35"
Overall Gage Width: 0.13"
Lot Number: 255

EA STRAIN GAGE

The EA strain gage is a general purpose constantan foil grid, epoxy backed strain gage (14). The following information is applicable to the EA strain gage used:

Manufacturer: Micro-Measurements, Inc.
Type: EA - 13 - 125AD - 120
Gage Resistance: 120.0 ± 0.15%
Gage Factor: 2.095 ± 0.5%

Overall Gage Length: 0.250"

Overall Gage Width: 0.125"

Lot Number: A14AF60

Fatigue Life: 10^5 cycles @ ± 1500 με

10^6 cycles @ ± 1000 με

S/N FATIGUE LIFE GAGES

The S/N fatigue gages are a constantan foil grid which is fully encapsulated in an epoxy resin system with glass filter reinforcement (8). The solder terminals are integral with the gage and the gages may come with or without the electrical leads attached. The following information is applicable to the S/N fatigue gages used, which were equipped with electrical leads:

Manufacturer: Micro-Measurements, Inc.

Type: FWA - 01

Gage Resistance: 100.0 ± 0.2% ohms

Gage Factor: varies with life of gage

Gage Integration Length: 0.250"

Gage Integration Width: 0.125"

Lot Numbers: ZD - A12AP29, ZD - A12AP21

Ti - 6Al - 4V TITANIUM ALLOY STOCK

All T-series specimens were fabricated from a 16 by 21-inch piece of 0.175-inch thick Ti - 6Al - 4V sheet. The following material specifications apply to this titanium sheet (18):

Processor: Titanium Metals Corporation of America

Yield Strength: longitudinal - 121,800 psi

transverse - 128,300 psi

Tensile Strength: longitudinal - 131,000 psi

transverse - 132,600 psi

Elongation: longitudinal - 16.5

transverse - 16.0

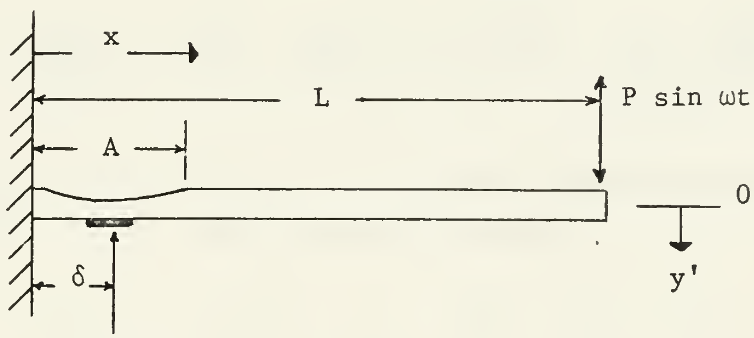
Heat Treatment: Annealing cycle consisting of an 8 hour hold at 1350°F followed by furnace cooling to 1000°F, then air cooling.

C. SAMPLE CALCULATIONS

Strain Calibration of Specimen

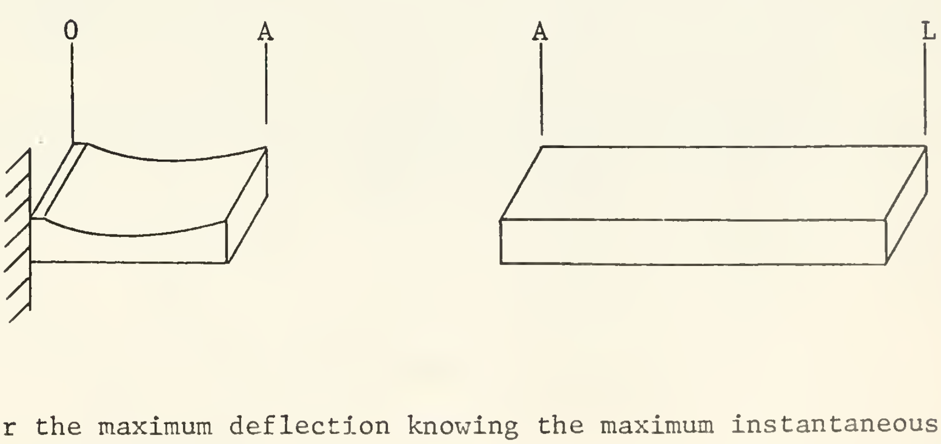
All specimens were cantilever beams which were subjected to reverse bending of constant amplitude. The beam is assumed to be a perfect cantilever beam (i.e., clamp connection is completely rigid) as shown in Figure XXIV.

Figure XXIV.



The specimen is considered as the two interrelated components indicated in Figure XXV below:

Figure XXV.



Solving for the maximum deflection knowing the maximum instantaneous bending moment of these two components:

$$EI\ y'' = \pm M \tag{1}$$

Realizing that $M = P(L - x)$, a substitution into equation (1) yields:

$$EI\ y'' = \pm P(L - x) \tag{2}$$

Integrating equation (2) will give:

$$EI\ y' = EI_1 \int_o^A y''\ dx + EI_2 \int_A^L y\ dx \tag{3}$$

Performing the integration above for each component and noting that $y' = 0$ when $x = 0$,

$$y(x)' = \pm \frac{P}{EI_1} (L\ x - \frac{x^2}{2})\quad 0 \leq x \leq A \tag{4}$$

$$y(x)' = \pm \frac{P}{EI_1} (LA - \frac{A^2}{2}) \pm \frac{P}{EI_2} \left[(L\ x - \frac{x^2}{2}) - (LA - \frac{A^2}{2}) \right] \quad A < x \leq L \tag{5}$$

Integrating again ($y = 0$ when $x = 0$), summing the two integrations $0 \leq x \leq A$ and $A < x \leq L$, and combining like terms:

$$y(x) = \pm \frac{P}{EI_1} \left\{ (1 - \frac{I_1}{I_2}) \left[(L-A)(LA - \frac{A^2}{2}) + (\frac{LA^2}{2} - \frac{A^3}{6}) \right] + (\frac{I_1}{I_2})(\frac{L^3}{3}) \right\} \tag{6}$$

Letting the terms within the brackets be represented by "B" i.e.,
$\left\{ (1 - I_1/I_2) \ . \ . \ . \right\} = B$

$$y = \pm \frac{PB}{EI_1} \tag{7}$$

Rearranging equation (7) yields:

$$P = \pm \frac{EI_1}{B} y \tag{8}$$

If δ = distance gage is from the support, then at the gage $M = P(L - \delta)$, and the elastic strain at the gage location is:

$$\varepsilon_g = \pm \frac{P(L - \delta)c}{EI_1} \tag{9}$$

Combining equations (8) and (9) yields:

$$\varepsilon_g = \pm \frac{EI_1 y\ \ (L - \delta)c}{B\ \ EI_1} \tag{10a}$$

$$\varepsilon_g = \pm \frac{y\, c\, (L - \delta)}{B} \tag{10b}$$

It is apparent from equation (10b) that the strain at the gage is independent of the material and dependent upon the geometry of the specimen and location of the gage. Equation (10b) differs considerably with the calculated strain equation of Johnson (8) which assumes each specimen is a prismatic beam.

A graphical comparison of the observed strain measurements versus calculated strain for the clamping block in positions 1, 2 and 3A/B is given in Figure III. The deviation of the calculated versus observed strain line from 45° is believed to be caused by the non-uniformity of the test specimens. The near zero intercept of the calculated versus observed strain line at the origin is considered well within experimental error.

Strain calibration results (observed and calculated) are tabulated in Table II.

TABLE II

STRAIN CALIBRATION

Function	Units	Block Positions 1	2	3
δ	inches	0.50	0.50	0.50
y	inches	0.10	0.10	0.10
A	inches	0.90	0.90	0.90
L	inches	3.90	3.15	2.40
c	inches	0.057	0.057	0.057
ε_c	$\mu\varepsilon$	- 1615	- 2270	- 3382
ε_t	$\mu\varepsilon$	+ 1888	+ 2455	+ 3679
ε_T	$\mu\varepsilon$	3503	4725	7061
$E_{R\text{-}obs}$	$\mu\varepsilon$	$\pm$ 1751	$\pm$ 2362	$\pm$ 3530
$\varepsilon_{R\text{-}calc}$	$\mu\varepsilon$	$\pm$ 1350	$\pm$ 1880	$\pm$ 2840

Gage Resistance Change

The Budd portable strain indicator was used to measure all changes in gage resistance. This indicator is a wheatstone bridge null-balance instrument which measures resistance change in units of strain (micro-inches per inch).

When the Basic Potentiometric Circuit relationships as set forth by Murray (12) are consolidated for a single active fatigue/strain gage, the following expression relates the indicated strain, gage factor setting and resistance change for the null-balance indicator:

$$\Delta\varepsilon_i = \frac{\Delta R}{Rg} \times \frac{1}{(GF)} \tag{11}$$

The basic circuit used was a wheatstone half-bridge with Rg in one leg and a decade box to insert a dummy value of Rg in the opposite leg. The gage factor dial was set at 2.00 for ease in calculations.

For values of ΔR less than 2 ohms, Rg may be assumed to be essentially constant and the following expression was used to determine ΔR:

$$\Delta R = (\Delta\varepsilon_i)\ Rg\ (GF) \tag{12}$$

As ΔR increased above 2 ohms, equation (12) could no longer be used due to the increased importance of circuit non-linearity. The relationship between actual and indicated ΔR and circuit non-linearity is given by the following(6):

$$(\Delta R/Rg)_{ind.} = (\Delta R/Rg)_{act.}\ (1 - n) \tag{13}$$

where $$(1 - n) \approx (1 - \Delta\varepsilon_i) \tag{14}$$

and therefore:

$$\left(\frac{\Delta R}{Rg}\right)_{act.} = \left(\frac{\Delta R}{Rg}\right)_{ind.} \frac{1}{(1-\Delta\varepsilon_i)} \tag{15}$$

Rearranging equation (15) and combining with equation (11) will yield the final expression which was used for all values of ΔR from 2 ohms to 10 ohms:

$$\Delta R = (\Delta \varepsilon_i)\ Rg\ (GF)\ (1 + \Delta \varepsilon_i) \tag{16}$$

In those instances when ΔR increased above 10 ohms, which was beyond the range of meaningful data and gage usefulness (16), the dummy value of Rg was adjusted in the Potentiometric Circuit. The circuit non-linearity was reduced to zero once more and equation (12) was used to determine the S/N fatigue gage resistance change.

D. TABULATION OF DATA

TEST # 1: Clamping Block Calibration of Position No. 1 for Reverse Bending

Material: Aluminum 2024 - T4

Design: Notched Fatigue Specimen - Type No. 1

Serial No.: A-1

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FAE - 25 - 12 S 13 Lot: 255

Gage Factor Setting: 2.04

Temperature: 76°F

Type Loading: Reverse Bending

Block Position	ε_c*	ε_t	ε_T	ε_R	x	y	L
1	- 1528	2975	4503	± 2252	0.50"	0.10"	3.90"

TEST # 2: Clamping Block Position Calibration for Reverse Bending

Material: Titanium Ti - 6 Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T-1

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: EA-13-125AD-120 Lot: A14AF60

Gage Factor Setting: 2.095

Temperature: 76°F

Type Loading: Reverse Bending

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* All strain measurements in Tabulation of Data will be given in microstrain.

Block Position	ε_c	ε_t	ε_T	ε_R	x	y	L
1	- 1615	1888	3503	± 1751	0.50"	0.10"	3.90"
2	- 2270	2455	4725	± 2362	0.50"	0.10"	3.15"
3A	- 3130	3539	6669	± 3334	0.50"	0.10"	2.40"
3B	- 3060	3942	7002	± 3501	0.50"	0.10"	2.40"

<u>TEST # 3:</u> S/N Fatigue Data

Material: Aluminum 2024 - T4

Design: Notched Fatigue Specimen - Type No. 1

Serial No.: A-2

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA-01 Lot: ZD-A12AP29

Gage Factor Setting: 2.095

Temperature: 72°F

Clamping Block Position: 1

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR
0	99.90	0.00
1	99.90	0.00
5	99.91	0.01
10	99.92	0.02
500	100.20	0.30
1,000	100.40	0.50
2,000	100.73	0.83
5,000	101.41	1.51
10,000	102.10	2.20
15,000	102.58	2.68
20,000	102.91	3.01
25,000	103.13	3.23
30,000	103.36	3.46
35,000	103.55	3.65
40,000	103.71	3.81
45,000	103.86	3.96
50,000	104.00	4.10
60,000	104.25	4.35
70,000	104.58	4.68
90,000	104.92	5.02
100,000	105.16	5.26
110,000	105.32	5.42

Cycle	Rg	ΔR	
120,000	105.48	5.58	
140,000	105.82	5.92	Specimen crack beside gage.
150,000	106.13	6.23	
160,000	106.50	6.60	
180,000	107.17	7.27	
190,000	107.52	7.62	
200,000	107.85	7.95	
210,000	108.23	8.33	
220,000	108.60	8.70	
240,000	109.30	9.40	
260,000	109.85	9.95	
305,000	112.27	12.37	
325,000	113.20	13.30	
370,000	118.12	18.22	
400,000	120.90	21.00	
450,000	126.10	26.20	Test terminated - large crack in specimen .

<u>TEST # 4:</u> S/N Fatigue Data

Material: Titanium Ti - 6 Al - 4 V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 2

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA-01 Lot: ZD-A12AP29

Gage Factor Setting: 2.00

Temperature: 75°F

Clamping Block Positions: 1 - 2 - 1 - 2 - 1 - 2

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 1
190	100.07	0.07	
250	100.08	0.08	
300	100.10	0.10	
400	100.12	0.12	
500	100.14	0.14	
700	100.18	0.18	
900	100.22	0.22	
1,000	100.24	0.24	
2,000	100.40	0.40	

Cycle	Rg	ΔR	
3,000	100.53	0.53	
5,000	100.76	0.76	
7,000	100.95	0.95	
9,000	101.11	1.11	
10,000	101.18	1.18	
15,000	102.36	2.36	In Position 2
20,000	103.08	3.08	
22,000	103.27	3.27	
24,000	103.43	3.43	
26,000	103.60	3.60	
30,000	103.88	3.88	
35,000	104.05	4.05	In Position 1
40,000	104.07	4.07	
45,000	104.11	4.11	
50,000	104.14	4.14	
55,000	104.25	4.25	In Position 2
60,000	104.51	4.51	
65,000	104.72	4.72	
70,000	104.90	4.90	
75,000	105.13	5.13	In Position 1
80,000	105.13	5.13	
85,000	105.16	5.16	
90,000	105.19	5.19	
95,000	105.25	5.25	In Position 2
100,000	105.50	5.50	
105,000	105.70	5.70	
110,000	105.88	5.88	
120,000	106.25	6.25	
130,000	106.61	6.61	
135,000	106.83	6.83	
140,000	107.04	7.04	
150,000	107.35	7.35	
160,500	107.65	7.65	
180,000	108.30	8.30	
200,000	108.95	8.95	Test terminated - insufficient gage performance data available.

TEST # 5: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 3

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP29

Gage Factor Setting: 2.00

Temperature: 76°F

Clamping Block Positions: 2 - 1 - 2 - 1 - 2 - 1

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 2
1	100.00	0.00	
2	100.01	0.01	
3	100.01	0.01	
4	100.01	0.01	
5	100.02	0.02	
8	100.02	0.02	
10	100.02	0.02	
20	100.04	0.04	
30	100.06	0.06	
40	100.06	0.06	
50	100.08	0.08	
100	100.12	0.12	
150	100.18	0.18	
190	100.21	0.21	
250	100.25	0.25	
300	100.28	0.28	
400	100.35	0.35	
500	100.42	0.42	
600	100.48	0.48	
900	100.64	0.64	
1,000	100.70	0.70	
1,500	100.91	0.91	
2,000	101.12	1.12	
3,000	101.46	1.46	
4,000	101.77	1.77	
5,000	102.02	2.02	
7,000	102.41	2.41	
8,000	102.60	2.60	
10,048	102.90	2.90	
10,049	102.88	2.88	In Position 1
15,000	102.96	2.96	
20,000	103.03	3.03	

Cycle	Rg	ΔR	
25,000	103.11	3.11	
30,000	103.17	3.17	
35,000	103.66	3.66	In Position 2
40,000	104.02	4.02	
45,000	104.30	4.30	
50,000	104.55	4.55	
55,000	104.57	4.57	In Position 1
60,000	104.60	4.60	
65,000	104.63	4.63	
70,000	104.66	4.66	
75,000	104.92	4.92	In Position 2
80,000	105.17	5.17	
85,000	105.38	5.38	
90,000	105.60	5.60	
95,000	105.63	5.63	In Position 1
100,000	105.67	5.67	
120,000	105.82	5.82	
140,000	105.97	5.97	
160,000	106.12	6.12	
182,000	106.29	6.29	
200,000	106.44	6.44	Test terminated - insufficient gage performance date available.

<u>TEST # 6:</u> S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 4

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP29

Gage Factor Setting: 2.00

Temperature: 76°F

Clamping Block Positions: 1 - 3A

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 1
1	100.00	0.00	
2	100.00	0.00	
3	100.01	0.01	
4	100.00	0.00	
5	100.01	0.01	
10	100.01	0.01	
15	100.01	0.01	
20	100.02	0.02	
30	100.02	0.02	
40	100.02	0.02	
50	100.03	0.03	
70	100.03	0.03	
85	100.04	0.04	
100	100.04	0.04	
150	100.06	0.06	
200	100.07	0.07	
300	100.10	0.10	
500	100.14	0.14	
750	100.19	0.19	
1,000	100.23	0.23	
1,500	100.31	0.31	
2,000	100.38	0.38	
3,000	100.50	0.50	
4,000	100.62	0.62	
5,000	100.71	0.71	
6,000	100.81	0.81	
7,000	100.89	0.89	
8,000	100.96	0.96	
8,250	100.98	0.98	
8,400	100.99	0.99	
8,500	101.00	1.00	
8,600	101.20	1.20	In Position 3A
8,720	101.38	1.38	
8,840	101.52	1.52	
9,340	102.11	2.11	
9,640	102.38	2.38	
9,840	102.55	2.55	
10,140	102.78	2.78	
10,340	102.91	2.91	
10,440	102.98	2.98	
10,530	103.04	3.04	
11,040	103.33	3.33	
11,540	103.56	3.56	
12,040	103.80	3.80	
13,040	104.18	4.18	
14,040	104.48	4.48	
15,040	104.73	4.73	
16,040	104.95	4.95	
17,040	105.13	5.13	
18,040	105.32	5.32	

Cycle	Rg	ΔR	
20,040	105.62	5.62	
23,040	105.97	5.97	
25,040	106.16	6.16	
28,040	106.45	6.45	
31,040	106.71	6.71	
36,040	107.17	7.17	
38,040	107.32	7.32	
42,040	107.63	7.63	
48,040	-	-	Gage failed - tab cracked at solder turret.

<u>TEST # 7:</u> S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 5

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP29

Gage Factor Setting: 2.00

Temperature: 76°F

Clamping Block Positions: 3A - 1 - 3A

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3A
1	100.01	0.01	
2	100.01	0.01	
3	100.02	0.02	
4	100.02	0.02	
5	100.02	0.02	
10	100.03	0.03	
15	100.04	0.04	
20	100.04	0.04	
30	100.08	0.08	
40	100.10	0.10	
50	100.15	0.15	
70	100.20	0.20	
100	100.27	0.27	
150	100.38	0.38	
200	100.48	0.48	
300	100.68	0.68	
400	100.84	0.84	

Cycle	Rg	ΔR	
450	100.92	0.92	
480	100.97	0.97	
500	100.99	0.99	
1,000	101.04	1.04	In Position 1
2,000	101.15	1.15	
7,000	101.53	1.53	
10,000	101.69	1.69	
12,000	101.78	1.78	
17,000	102.02	2.02	
22,000	102.16	2.16	
32,000	102.37	2.37	
42,000	102.53	2.53	
52,000	102.68	2.68	
62,000	102.71	2.71	
72,000	102.82	2.82	
92,000	103.01	3.01	
103,000	103.09	3.09	
112,000	103.14	3.14	
122,000	103.21	3.21	
132,000	103.28	3.28	
162,000	103.46	3.46	
192,000	103.62	3.62	
212,000	103.72	3.72	
232,000	103.85	3.85	
258,000	104.01	4.01	
292,000	104.20	4.20	
312,000	104.33	4.33	
332,000	104.45	4.45	
335,000	104.48	4.48	In Position 3A
336,000	104.97	4.97	
337,000	105.33	5.33	
338,000	105.62	5.62	
339,000	105.87	5.87	
340,000	106.07	6.07	
342,000	106.44	6.44	
343,000	106.60	6.60	
346,000	107.00	7.00	
348,000	107.21	7.21	
350,000	107.43	7.43	
352,000	107.60	7.60	
356,000	107.82	7.82	
360,000	108.00	8.00	
364,000	108.59	8.59	
369,000	108.91	8.91	
374,000	109.24	9.24	
377,000	109.40	9.40	
379,000	110.25	10.25	
381,000	111.14	11.14	
382,000	111.59	11.59	Gage is failing. Readings erratic. Test discontinued.

TEST # 8: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 6

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP21

Gage Factor Setting: 2.00

Temperature: 79°F

Clamping Block Positions: 3B - 1 - 3B

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3B
1	100.02	0.02	
2	100.03	0.03	
3	100.03	0.03	
4	100.03	0.03	
5	100.04	0.04	
10	100.06	0.06	
15	100.09	0.09	
20	100.11	0.11	
30	100.14	0.14	
40	100.18	0.18	
50	100.21	0.21	
70	100.28	0.28	
100	100.37	0.37	
150	100.49	0.49	
200	100.61	0.61	
300	100.82	0.82	
350	100.91	0.91	
390	100.99	0.99	
400	101.01	1.01	
1,400	101.13	1.13	In Position 1
2,400	101.23	1.23	
7,400	101.56	1.56	
12,400	101.81	1.81	
17,400	102.00	2.00	
22,400	102.14	2.14	
27,400	102.25	2.25	
32,400	102.36	2.36	
37,400	102.43	2.43	
47,000	102.57	2.57	
57,000	102.70	2.70	
67,000	102.81	2.81	
77,000	102.90	2.90	

Cycle	Rg	ΔR	
87,000	102.98	2.98	
95,000	103.02	3.02	
97,000	103.04	3.04	
102,000	103.08	3.08	
122,000	103.20	3.20	
157,000	103.40	3.40	
202,000	103.61	3.61	
232,000	103.76	3.76	
267,000	103.91	3.91	
302,000	104.06	4.06	
322,000	104.17	4.17	
372,000	104.32	4.32	
412,000	104.47	4.47	
420,400	104.50	4.50	
420,800	104.76	4.76	In Position 3B
421,800	105.27	5.27	
422,800	105.68	5.68	
423,800	105.97	5.97	
424,800	106.25	6.25	
425,800	106.50	6.50	
426,800	106.72	6.72	
427,800	106.95	6.95	
429,800	107.63	7.63	
430,800	108.30	8.30	
431,800	-	-	Gage failed - both tabs cracked at solder turrets.

TEST # 9: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T-7

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA-01 Lot: ZD-A12AP21

Gage Factor Setting: 2.00

Temperature: 79°F

Clamping Block Positions: 1 - 2 - 3B - 1 - 3B

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 1
1	100.00	0.00	
4	100.00	0.00	
5	100.00	0.00	
8	100.00	0.00	
10	100.01	0.01	
15	100.01	0.01	
20	100.02	0.02	
30	100.02	0.02	
40	100.02	0.02	
50	100.03	0.03	
70	100.04	0.04	
86	100.04	0.04	
100	100.04	0.04	
150	100.06	0.06	
200	100.08	0.08	
300	100.10	0.10	
400	100.13	0.13	
500	100.15	0.15	
900	100.47	0.47	In Position 2
1,080	100.60	0.60	
1,280	100.70	0.70	
1,580	100.85	0.85	
1,880	101.00	1.00	
2,380	101.21	1.21	
3,380	101.57	1.57	
4,380	101.87	1.87	
5,380	102.17	2.17	
5,630	102.40	2.40	In Position 3B
5,880	102.64	2.64	
6,130	102.83	2.83	
6,380	103.05	3.05	
16,380	103.22	3.22	In Position 1
36,380	103.44	3.44	
56,380	103.58	3.58	
81,380	103.73	3.73	
106,380	103.85	3.85	
106,880	104.10	4.10	In Position 3B
107,380	104.33	4.33	
107,880	104.52	4.52	
108,380	104.81	4.81	
108,880	104.86	4.86	
110,880	105.43	5.43	
112,880	-	-	Gage failed - tab cracked at solder turret.

TEST # 10: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No.2

Serial No.: T - 8

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP21

Gage Factor Setting: 2.00

Temperature: 78°F

Clamping Block Positions: 3B - 2 - 1 - 3B

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3B
1	100.00	0.00	
2	100.01	0.01	
3	100.02	0.02	
4	100.02	0.02	
5	100.03	0.03	
7	100.04	0.04	
11	100.06	0.06	
15	100.07	0.07	
20	100.10	0.10	
25	100.12	0.12	
30	100.14	0.14	
34	100.16	0.16	
64	100.19	0.19	In Position 2
114	100.24	0.24	
314	100.40	0.40	
514	100.51	0.51	
714	100.64	0.64	
914	100.76	0.76	
1,414	101.00	1.00	
1,914	101.21	1.21	
2,914	101.57	1.57	
4,914	102.13	2.13	
6,914	102.20	2.20	In Position 1
16,914	102.47	2.47	
26,914	102.65	2.65	
46,914	102.95	2.95	
66,914	103.05	3.05	
81,914	103.17	3.17	
82,837	103.73	3.73	In Position 3B
83,214	103.95	3.95	
84,214	104.35	4.35	
85,214	104.78	4.78	

Cycle	Rg	ΔR	
86,214	104.93	4.93	
87,214	105.17	5.17	
88,214	105.37	5.37	
90,214	105.77	5.77	
92,214	107.19	7.19	
92,250	-	-	Gage failed - tab cracked at solder turret.

TEST # 11: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No.2

Serial No.: T - 9

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP21

Gage Factor Setting: 2.00

Temperature: 80°F

Clamping Block Positions: 1 - 2 - 3B

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 1
1	100.00	0.00	
2	100.00	0.00	
3	100.00	0.00	
5	100.01	0.01	
7	100.01	0.01	
10	100.01	0.01	
15	100.01	0.01	
20	100.01	0.01	
30	100.02	0.02	
60	100.03	0.03	
80	100.04	0.04	
100	100.05	0.05	
166	100.05	0.05	
200	100.07	0.07	
300	100.10	0.10	
500	100.14	0.14	
700	100.18	0.18	
1,000	100.24	0.24	
1,500	100.32	0.32	
2,200	100.42	0.42	
3,000	100.53	0.53	

Cycle	Rg	ΔR	
5,000	100.74	0.74	
5,500	100.99	0.99	In Position 2
6,000	101.21	1.21	
7,000	101.58	1.58	
8,000	101.97	1.97	
9,000	102.11	2.11	
9,500	102.57	2.57	In Position 3B
10,000	103.01	3.01	
11,000	103.62	3.62	
12,000	104.05	4.05	
13,000	104.43	4.43	
15,000	104.92	4.92	
18,000	-	-	Gage failed - both tabs cracked at solder turrets.

<u>TEST # 12:</u> S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No. 2

Serial No.: T - 10

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA - 01 Lot: ZD - A12AP21

Gage Factor Setting: 2.00

Temperature: 80°F

Clamping Block Positions: 3B - 2 - 1 - 3B - 2 - 3B

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3B
1	100.00	0.00	
2	100.01	0.01	
3	100.02	0.02	
4	100.02	0.02	
5	100.03	0.03	
7	100.04	0.04	
9	100.05	0.05	
10	100.06	0.06	
15	100.08	0.08	
20	100.10	0.10	
26	100.12	0.12	
30	100.14	0.14	
34	100.15	0.15	

Cycle	Rg	ΔR	
64	100.18	0.18	In Position 2
114	100.23	0.23	
214	100.30	0.30	
414	100.44	0.44	
614	100.57	0.57	
914	100.73	0.73	
1,414	100.97	0.97	
1,914	101.18	1.18	
2,914	101.54	1.54	
4,914	102.08	2.08	
6,914	102.15	2.15	In Position 1
16,914	102.42	2.42	
36,914	102.74	2.74	
56,914	102.98	2.98	
81,914	103.16	3.16	
82,144	103.34	3.34	In Position 3B
82,314	103.44	3.44	
82,514	103.56	3.56	
82,714	103.68	3.68	
85,714	103.90	3.90	In Position 2
90,714	104.19	4.19	
95,714	104.42	4.42	
100,714	104.61	4.61	
110,714	104.94	4.94	
120,714	105.27	5.27	
123,714	105.38	5.38	
125,714	105.45	5.45	
130,714	105.60	5.60	
135,714	105.70	5.70	
136,214	105.83	5.83	In Position 3B
136,714	105.96	5.96	
137,214	106.10	6.10	
138,214	106.30	6.30	
140,214	106.72	6.72	
142,214	-	-	Gage failed - both tabs cracked at solder turrets.

TEST # 13: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No.2

Serial No.: T-11

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA-01 Lot: ZD-A12AP21

Gage Factor Setting: 2.00

Temperature: 80°F

Clamping Block Positions: 3B - 2 - 1 - 3B - 2

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM (exception: manual bending when cycle interval is less than 10)

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3B
1	100.00	0.00	
2	100.01	0.01	
3	100.02	0.02	
5	100.03	0.03	
10	100.05	0.05	
15	100.08	0.08	
20	100.10	0.10	
30	100.14	0.14	
50	100.21	0.21	
70	100.28	0.28	
100	100.37	0.37	
150	100.50	0.50	
200	100.62	0.62	
600	101.37	1.37	
1,000	101.92	1.92	
1,050	101.98	1.98	
1,061	101.99	1.99	
1,062	101.99	1.99	
1,065	102.00	2.00	
1,065	101.99	1.99	In Position 2
1,066	101.99	1.99	
1,067	101.98	1.98	
1,068	101.98	1.98	
1,069	101.98	1.98	
1,070 - 1,155	101.98 - 101.99	1.98 - 1.99	ΔR remained essentially fixed (manual bending rate).
1,160	102.00	2.00	
1,250	102.04	2.04	
1,350	102.06	2.06	

Cycle	Rg	ΔR	
1,490	102.10	2.10	
2,600	102.60	2.60	
4,600	102.96	2.96	
5,000	103.00	3.00	
5,070	103.02	3.02	
5,072	103.02	3.02	
5,095	103.03	3.03	
5,145	103.04	3.04	
5,235	103.05	3.05	
5,236	103.02	3.02	In Position 1
5,237	103.02	3.02	
5,238	103.02	3.02	
5,239	103.02	3.02	
5,240 - 6,000	103.02 - 103.03	3.02 - 3.03	ΔR remained essentially fixed.
6,100	103.04	3.04	
6,400	103.06	3.06	
6,800	103.08	3.08	
9,000	103.10	3.10	
10,000	103.13	3.13	
10,800	103.15	3.15	
25,800	103.38	3.38	
30,800	103.46	3.46	
32,800	104.39	4.39	In Position 3B
33,994	104.45	4.45	
34,000	104.46	4.46	
34,010	104.46	4.46	
34,030	104.47	4.47	
34,050	104.48	4.48	
34,080	104.49	4.49	
34,101	104.50	4.50	
34,101	104.43	4.43	In Position 2
34,102	104.42	4.42	
34,103	104.41	4.41	
34,104	104.41	4.41	
34,105 - 34,430	104.42 - 104.43	4.42 - 4.43	ΔR remained essentially fixed.
34,650	104.45	4.45	
34,900	104.48	4.48	
35,000	104.49	4.49	
35,250	104.50	4.50	
35,300	104.50	4.50	
35,700	104.54	4.54	
36,200	104.57	4.57	
36,700	104.61	4.61	
47,000	105.10	5.10	
57,000	105.52	5.52	
67,000	105.82	5.82	
82,000	106.23	6.23	
102,000	106.66	6.66	

Cycle	Rg	ΔR	
122,000	107.05	7.05	
152,000	107.69	7.69	
182,000	108.00	8.00	
207,000	108.35	8.35	
237,000	108.70	8.70	
252,000	109.48	9.48	Gage appears to be failing. One solder tab cracked - NOT at solder turret.
262,000	109.85	9.85	
272,000	110.10	10.10	
322,000	111.25	11.25	
352,000	111.80	11.80	
402,000	112.59	12.59	
462,000	113.28	13.28	
500,000	113.70	13.70	
550,000	114.19	14.19	
600,000	114.66	14.66	
650,000	115.08	15.08	Test terminated, readings are drifting when taken.

TEST # 14: S/N Fatigue Data

Material: Titanium Ti - 6Al - 4V

Design: Notched Fatigue Specimen - Type No.2

Serial No.: T-12

Strain Indicator: Budd Portable Strain Indicator, Model P-350

Gage Type: FWA-01 Lot: ZD-A12AP21

Gage Factor Setting: 2.00

Temperature: 79°F

Clamping Block Positions: 3B - 2 - 1 - 3B - 2

Type Loading: Reverse Bending

Average Specimen Bending Rate: 1000 CPM (exception: manual bending when cycle interval is less than 10)

Cycle	Rg	ΔR	
0	100.00	0.00	In Position 3B
1	100.01	0.01	
2	100.01	0.01	
3	100.02	0.02	
5	100.03	0.03	
10	100.06	0.06	
15	100.08	0.08	
20	100.09	0.09	

Cycle	Rg	ΔR	
50	100.21	0.21	
100	100.37	0.37	
150	100.49	0.49	
200	100.62	0.62	
500	101.20	1.20	
900	101.79	1.79	
1,000	101.93	1.93	
1,050	102.00	2.00	
1,061	102.01	2.01	
1,065	102.01	2.01	
1,067	102.02	2.02	
1,067	102.01	2.01	In Position 2
1,068	102.00	2.00	
1,069	102.00	2.00	
1,070	102.00	2.00	
1,071	101.99	1.99	
1072 - 1,122	102.00 - 102.02	2.00 - 2.02	ΔR remained essentially fixed (manual bending rate).
1,123	102.02	2.02	
1,500	102.11	2.11	
2,000	102.26	2.26	
5,000	102.85	2.85	
6,000	103.00	3.00	
6,310	103.03	3.03	
6,400	103.05	3.05	
6,400	103.05	3.05	In Position 1
6,401	103.04	3.04	
6,402	103.04	3.04	
6,403	103.04	3.04	
6,404	103.04	3.04	
6,404 - 6,700	103.04	3.04	ΔR remained fixed.
6,900	103.04	3.04	
8,000	103.07	3.07	
10,000	103.11	3.11	
11,500	103.14	3.14	
15,000	103.20	3.20	
25,000	103.32	3.32	
37,000	103.44	3.44	
37,100	103.50	3.50	In Position 3B
38,500	104.14	4.14	
39,500	104.41	4.41	
39,850	104.50	4.50	
39,900	104.52	4.52	
39,950	104.52	4.52	
40,000	104.53	4.53	
40,050	104.55	4.55	
40,050	104.55	4.55	In Position 2
40,055	104.54	4.54	
40,060	104.53	4.53	

Cycle	Rg	ΔR	
40,065	104.54	4.54	
40,065 - 40,400	104.54 - 104.55		
		4.54 - 4.55	ΔR remained essentially fixed.
40,600	104.55	4.55	
41,000	104.57	4.57	
42,700	104.67	4.67	
55,000	105.09	5.09	
70,000	105.40	5.40	
111,000	105.90	5.90	
155,000	106.28	6.28	
205,000	106.60	6.60	
285,000	106.98	6.98	
375,000	107.35	7.35	
457,000	107.62	7.62	
500,000	107.78	7.78	
555,000	107.93	7.93	
625,000	108.54	8.54	
685,000	108.90	8.90	
735,000	109.15	9.15	
815,000	109.50	9.50	
885,000	109.86	9.86	
935,000	110.10	10.10	
1,000,000	110.40	10.40	Insufficient gage performance data beyond 10^6 cycles and ΔR > 10.0 ohms.
1,100,000	115.27	15.27	
1,160,000	119.98	19.98	
1,215,000	142.63	42.63	
1,250,000	159.47	59.47	
1,290,000	173.83	73.83	
1,330,100	266.71	166.71	A partial crack observed across each solder tab at solder turret.
1,330,100	-	-	Gage failed - both tabs completely cracked.

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